LONGITUDINAL AND TRANSVERSE COMPRESSION TESTS ON THIN-WALLED FIBRE REINFORCED COMPOSITE PIPE FOR OIL AND GAS FIELD DEPLOYMENT

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Abstract
This work conducted the mechanical testing of composites done to analyze the behaviour of a composite pipe. However, mechanical testing was limited to compression conducted on a thin-walled carbon fibre reinforced plastic pipe. Compression tests in the longitudinal and transverse directions, was carried out on thin-walled fibre reinforced composite pipe with an external diameter of 10 ± 0.01 mm and wall thickness of 1 ± 0.05 mm in the laboratory based on the ASTM D695, ISO 604 compression test standards, using the Instron machine 4483 to determine the modulus and compressive strength of a unidirectional composite pipe when subjected to uniaxial compressive loading at a constant rate. Longitudinal compression test results show an average fracture load of 14.15kN, maximum displacement of 0.3mm, yield stress of 0.49kN and stiffness of 42.8kN/mm. Transverse compression results showed an average maximum break load of 0.082kN and very low displacement. Overall, composites exhibit anisotropic characteristics under tension and compression unlike monolithic materials. The varying results shown in this study focused on their ability to withstand varying loads in tension, lateral compression and longitudinal compression prove this assertion. Compression results in the longitudinal direction also reiterate the ability of composites to withstand high loads and stress. This is as a result of loading along the fibre arrangement. This work shows the need for proactive testing of composites before deploying to the field to ascertain their behavior and strength characteristics under loading.

Keywords: Mechanical testing, Compression tests, Composite pipe, Carbon-fibre, Instron machine, Oil and Gas.

Introduction
Historical accounts show that before modern applications of composites, man has applied innovative ways of using composite materials. Israelites before Christ understood that clay, reinforced with straw could be used in constructing buildings and structures which have lasted, some even to this present day. Other major examples include the invention of writing materials from the papyrus plant (4000 B.C.) (Herakovich, 1998), the use of bamboo shoots as reinforcements in mud walls, glued laminated wood by Egyptians (1500B.C.), as well as laminated metals in forging swords (A.D. 1800) (Kaw, 2005). Composite is a general word used for a compound composed of at least two distinct materials with different properties. These materials are often designed to work together to deliver better performance in terms of strength, stiffness, durability and so on.

With the rapid development of industries and technology, the world's energy consumption has substantially increased (Obaseki & Elijah, 2020). As long as significant offshore hydrocarbon reserves are still being found, offshore oil and gas production will continue to play a significant role in energy supply, at least to under developed and even developing countries (Elijah & Etebu, 2019; Okoro, 2020; Elijah, *et al.*, 2020). However, the transportation of hydrocarbon products is an important issue (Obaseki *et al.* 2020a; Obaseki *et al.*, 2020b). Generally, offshore pipelines have been considered one of the most economical means of large scale oil and gas transportation as they are commonly believed to be more energy efficient than other means of transportation (Elijah & Obaseki, 2020).

Pipelines are widely used in the oil and gas industry in both offshore and onshore operations. After several years of operation corrosive environments, existing steel pipelines may suffer from internal or external metal loss due to erosion and/or corrosion damage mechanisms (Obaseki *et al.*, 2020a; Obaseki *et al.*, 2020b; Obaseki & Elijah, 2020). More than 60 percent of the world's oil and gas transmission pipelines are more than 40 years old (Mohitpour *et al.*, 2001). The deployment of a good composite material would solve this issue by ensuring long term integrity of the assets.

In recent years, the use of engineering composite materials has been growing significantly in a wide range of industrial sectors, such as the Oil and Gas (Williams & Sas-Jaworsky, 2000; Campbell, 2010; Yi *et al.*, 2010). The first applications were to develop systems that protect metal structures against events such as fire, explosions, and impact. From there, the number of applications has increased to cover elements such as piping systems on land and offshore, storage tanks and containers, structural reinforcements of platforms, among others. Composite pipelines have numerous competitive advantages over metal pipelines for the transportation of gas, oil or multi-phase fluids, as well as applications requiring high-pressure water or CO_2 injection (Williams & Sas-Jaworsky, 2000). The costs of installation, operation and maintenance are considerably reduced because they are sold in rolls up to 2740 m, which require less personnel and equipment for installation, do not use welding, coatings or X-rays and, most importantly, do not present corrosion. The assembly of this technology has been designed to be faster, safer and with less impact to the environment. Composites have been used in many structural and engineering applications for a long time. Companies in the oil and gas sector are now introducing composite pipes to replace existing metal pipes and installing new lines. It is estimated that in the medium term, the percentage of use of composite materials will exceed conventional pipe technology for the transportation of hydrocarbons (Padmavathi *et al.*, 2012). However, structural integrity and the remaining life is more complicated than in steel, due to the anisotropic properties of the reinforcing layer (Hexcel Corporation, 2014). This study is important because it addresses a pressing need for a very sensitive productive sector in the economy of several countries (including Nigeria), such as oil and gas. In this paper, mechanical testing was limited to compression test conducted on a thin-walled carbon fibre reinforced plastic pipe. Compression tests in the longitudinal and transverse directions were carried out on thin-walled fibre reinforced composite pipe with an external diameter of (10 ± 0.01) mm and wall thickness of (1 ± 0.05) mm in the laboratory based on the ASTM D695, ISO 604 compression test standards, using the Instron machine 4483 to determine the compressive modulus and strength of a unidirectional composite pipe when subjected to uniaxial compressive loading at a constant rate. In the course of the work, mechanical testing of carbon fibre composite pipes using Instron machine was conducted and based on the test results, the maximum load carbon fibre composite pipes can withstand before failure by compression was ascertained.

Materials And Methods

Materials

Instron 4483 machine in a laboratory in Port Harcourt, Rivers State of southern Nigeria was used. Composite pipe from a thin-walled carbon fibre reinforced plastic pipe was obtained from GAP international limited, Warri, Delta State, Nigeria.

Methods

In this paper, compression test was selected to analyse the mechanical properties of a thin-walled carbon fibre reinforced composite pipe when subjected to stresses. Compression tests were conducted in the longitudinal and transverse directions of the pipe. Compression tests are used to understand the behaviour of composite materials (elastic limit, proportionality limit, yield point, yield strength and compressive strength) under compressive loads or forces. They are also complementary tests to tensile tests, but are very important when applied to composites (Rathnaweera *et al*., 2011). They are also easier to perform and do not require complex apparatus. Because of the anisotropic nature of composites, they usually have differing strengths in tension and compression. Unidirectional fibres show higher compression strengths along the fibre or in the longitudinal direction as opposed to the transverse direction.

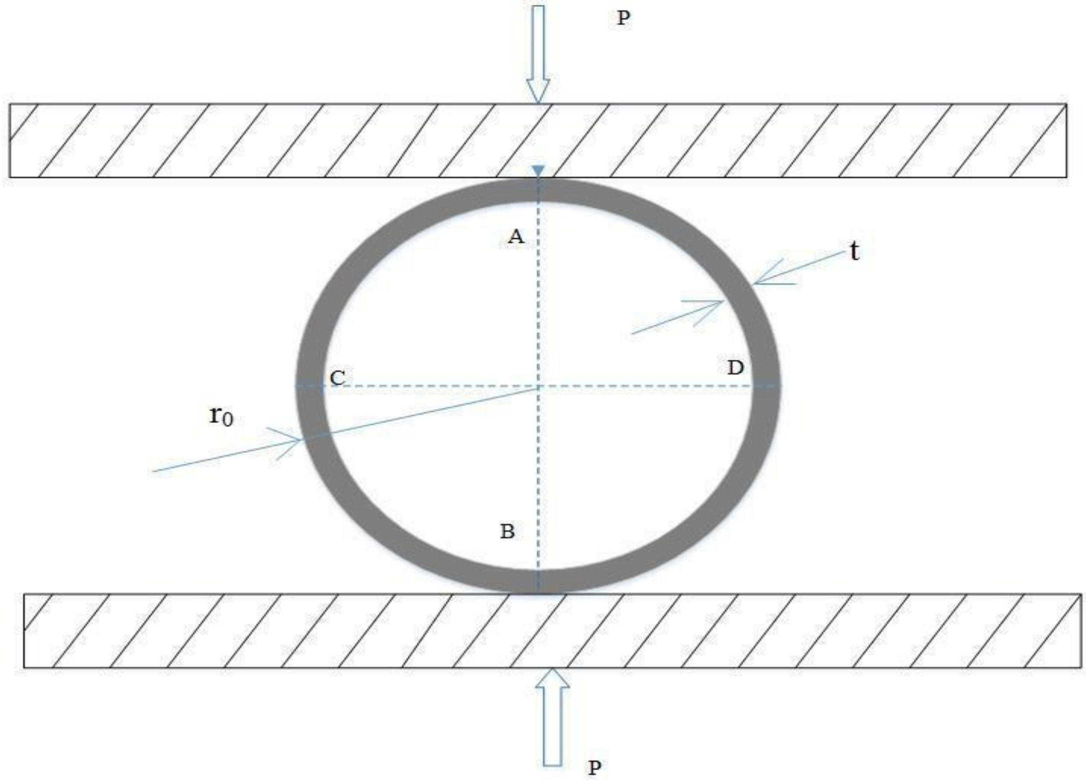

Figure 1: Schematic of the lateral compression test.

Figure 1 shows a schematic diagram of the test procedure. In this paper, compression tests were carried out on thin-walled fibre reinforced plastics in the longitudinal and transverse directions using the Instron machine 4483 and to avoid buckling, the sample ratio of length to diameter was 2.

Test Apparatus and Specimen

For both compression tests, a (20 ± 0.25) mm long composite pipe with an external diameter of (10 ± 0.01) mm and wall thickness of (1 ± 0.05) mm was used. Both tests were conducted on the Instron 4483 machine. The compression load was assumed to be perpendicular to the surface of each sample used. The crosshead speed used in both tests was 1 mm/min while the data computation rate was 2.0 pts/sec. The platens were separated by 20 mm to allow for adequate space for the specimen in both tests. The test is based on the ASTM D695, ISO 604 compression test standards.

Test Procedure

1. Visual inspection of the pipe to ensure no damage was done to the pipe prior to testing.
2. Six pipe specimens were prepared by cutting the pipe into 20 mm using an electric saw.

3. Diameter and thickness of the pipe were measured using Vernier calipers.
4. Mount the upper platen.
5. Mount the lower platen.
6. Select the Compression test method on the machine and input specimen dimensions and measurement parameters.
7. Place the specimen between the two platens.
8. Manually lower the top assembly till the top platen touches the face of the pipe without any load.
9. Reset the loading parameter to zero load on the machine.
10. Place protective glass shield and wear goggles.
11. Begin Compressive test.

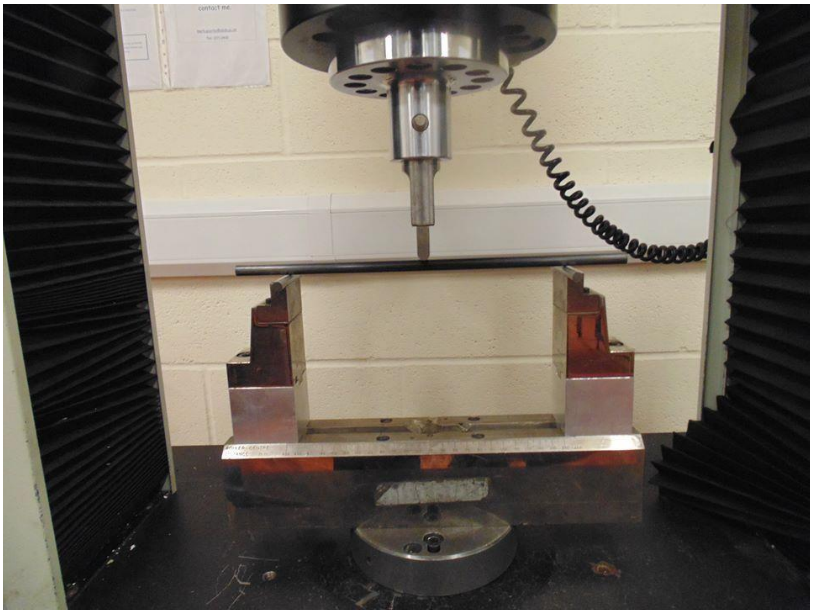

Plate 1: Compression tests carried out on thin-walled fibre reinforced plastics in the longitudinal and transverse directions.

Test results were computed by the machine during the test period. After the test was completed, results were saved and extracted while the machine was safely turned off.
Some of the equations used to obtain results are as follows (Rathnaweera *et al.*, 2011):

$$\sigma_f = \frac{M}{Z} \tag{1}$$

$$\varepsilon = \frac{y}{\rho} \tag{2}$$

Equations (1) and (2) were used to calculate stress and strain.
Where σ_f = bending stress, M = bending moment I = moment of inertia I and Z= sectional modulus of the pipe, ρ= radius of curvature, y= maximum displacement from the neutral axis and ε = strain.

$$\varepsilon E = \sigma \tag{3}$$

To obtain the value of bending stiffness K, the calculated young's modulus is multiplied by the moment of inertia of the pipe, thus:

$$K = EI \tag{4}$$

To calculate the strain energy of the pipe U, the area under the stress-strain curve for which the pipe obeys a linear relationship is taken, thus:

$$U = \int \sigma d\varepsilon \tag{5}$$

Stress and Strain were calculated, thus:

$$\sigma = \frac{P}{A} \quad (6)$$

$$\varepsilon = \frac{y}{L} \quad (7)$$

Where P=force, A=cross-sectional area, y=displacement under compression, L=length of pipe. A plot of stress and strain was also plotted while these parameters were used to calculate the Young's modulus of the material using Hooke's law.
Stiffness was also calculated using Equation (8) by taking a value of load and dividing by its corresponding value of displacement, thus:

$$K = \frac{P}{y} \quad (8)$$

Where P= load and y= deflection.
K can also be calculated using Equation (9).

$$K = \frac{AE}{L} \quad (9)$$

Where A= cross-sectional area, E= Young's modulus, and L=length of pipe.
Aside estimate from test/experiment, Equation (10) can also be used to calculate the stress results (Rathnaweera *et al.*, 2011).

$$\sigma_y = \frac{\alpha P_l r_o}{t^2 l} \quad (10)$$

Where α = 1.0 if $l \le xt$ ($1 \le x \le 5$) and α = 0.866 if $l > 2r_o$, P_l= limit load, r_o= external radius, t = thickness.

According to Rathnaweera *et al.*, (2011), the compressive modulus for pipes subjected to transverse loading can be calculated using Equation (11).

$$E = \frac{12P_e r_o^3 \beta}{\delta t^3 l}\left(\frac{\pi}{4} - \frac{2}{\pi}\right) \quad (11)$$

Where, β = 1 − v2 for plane strain conditions and β = 1.0 for plane stress conditions (Rathnaweera *et al.*, 2011).

Results and Discussion

Data for the loads and corresponding compressive strain computed from the Instron machine was retrieved and analysed using Microsoft Excel software. From the plot of these data the compressive strength, yield strength, offset yield strength as well as the Modulus of elasticity is easily estimated.

Table 1: Longitudinal Compression Test Results

Material	Break Load (kN)	Maximum Displacement (mm)	Yield stress σ (kN/mm)	Maximum Strain (mm/mm)	Stiffness (kN/mm)
Specimen 1	14.93	0.31	0.52	0.015	46.66
Specimen 2	14.75	0.30	0.52	0.015	47.60
Specimen 3	12.76	0.28	0.45	0.014	42.84
Average	14.15	0.30	0.50	0.015	45.700

Longitudinal Compression Test Results

Three composite pipes were subjected to compressive loads carried out on the Instron 4483 machine. Distance between the platens was about 20 mm. The top platen moved at a constant speed of 1mm/min. The load-deflection values were obtained and a graph of load-deflection was plotted (see Figures 2, 3, 5 and 6).

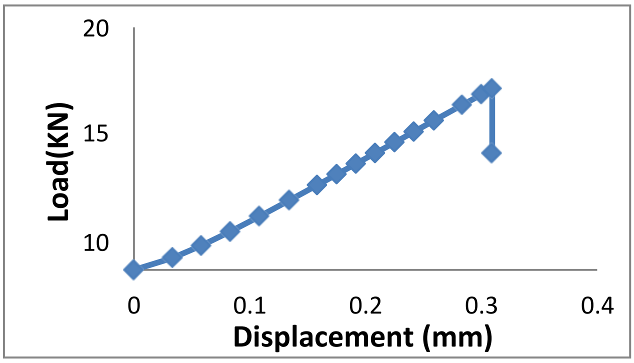

Figure 2A: Load displacement graphs of specimen 1

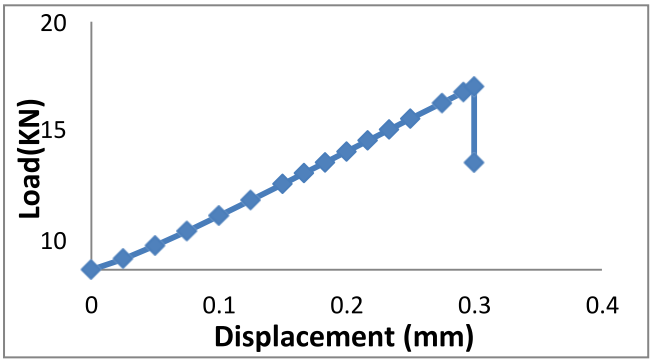

Figure 2B: Load displacement graphs of specimen 2

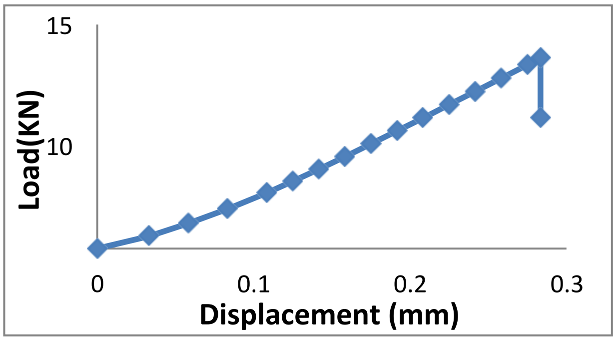

Figure 2C: Load displacement graphs of specimen 3

Figures 2A to 2C depict the load-displacement plot from Instron machine for three different specimens.

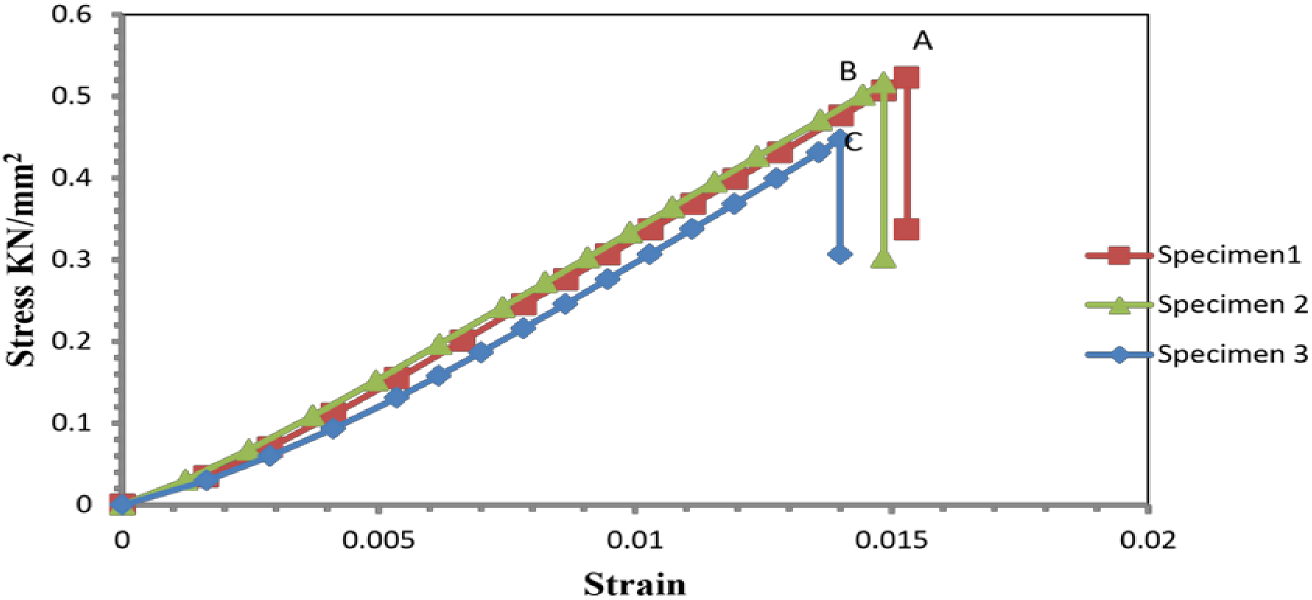

Figure 3: Stress-Strain graph of three specimens

From Figures 2A to 2C, the stress and strain were calculated by using Equations (6) and (7). The average yield strength of all specimens was calculated and found to be 0.49kN. Stiffness was also calculated using Equation (8) and was obtained as 42.8kN/mm by taking a value of load, and dividing by its corresponding value of displacement. Longitudinal compression test results show an average fracture load of 14.15kN, maximum displacement of 0.3mm. Transverse compression results showed an average maximum break load of 0.082kN and very low displacement in terms of Young's modulus, K can also be calculated using Equation (9).

Lateral Compression Test Results

Lateral or transverse compression tests were also carried out on three thin-walled carbon fibre composite pipes using the Instron machine 4483 at a velocity of 1mm/min in the laboratory.

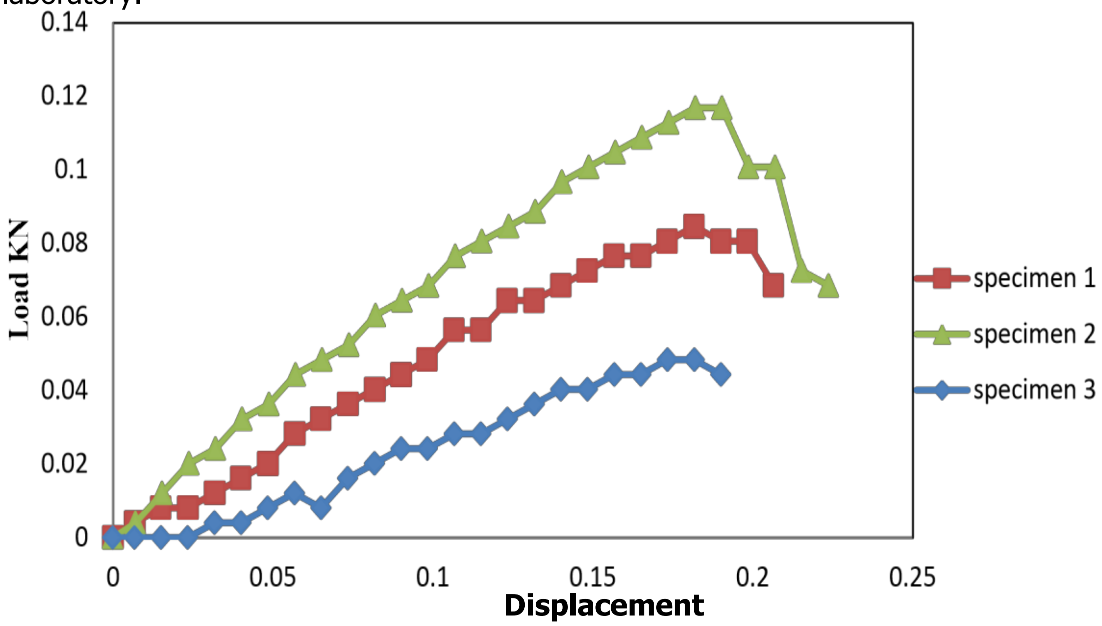

Figure 5: Load displacement graph of carbon fibre pipes under transverse compression loading

Load and displacement results were computed, and a graph (Figure 5) was plotted to show the deflection of the composite pipe under loading. Equation (10) can also be used to obtain the stress results (Rathnaweera *et al.*, 2011).

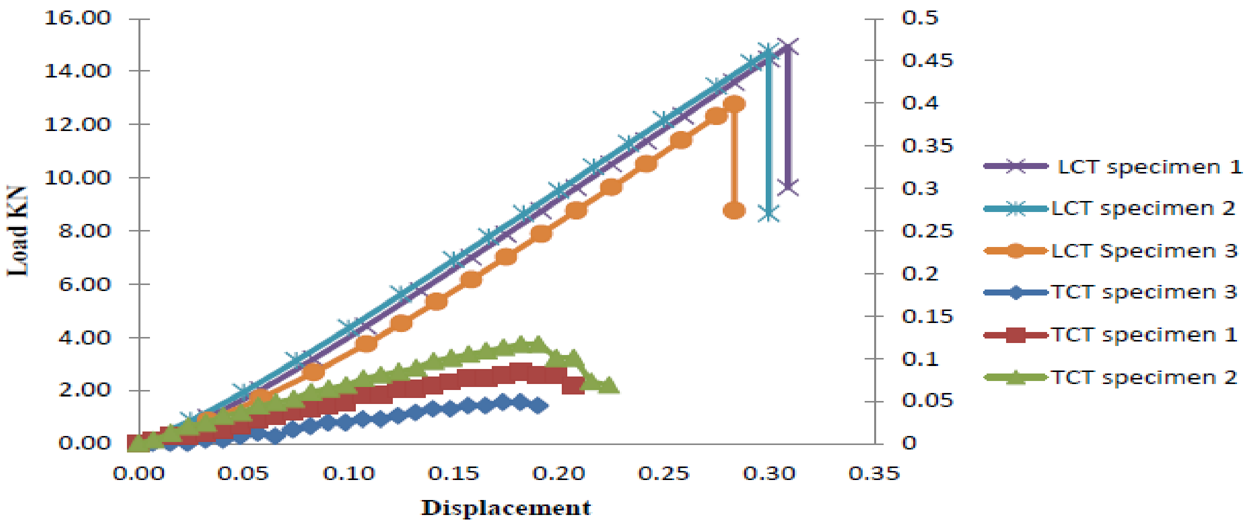

Figure 6: Load-displacement plots of longitudinal and transverse compression test

It was noticed that the average maximum load was 0.082kN and that the pipe did not undergo much displacement. It collapsed early and under low loads.

Discussion

To understand the characteristics of carbon fibre pipes, the pipe was subjected to uniaxial compressive loading in the longitudinal direction and in the transverse directions. Three samples were used in each test and for each stress-strain graph shown; the compressive strength of the carbon fibre pipe can be seen at the highest point (B).

For the three specimens tested in the longitudinal direction, high values of load and stress were gotten. This was expected because the load was applied along the fibre arrangement within the matrix of the pipe. Specimen 1 and 2 barreled under compression while specimen 3 experienced a complete fracture under compression.

The other three composite pipes subjected to transverse loading showed very low values of load and stress. This was expected because the compressive loads were applied across the fiber arrangement within the matrix of the pipe. All three specimens fractured under this test, while specimen 1 and 2 experienced a linear relationship between stress and strain until the fracture point. Specimen 3 however, showed a slight deflection from the expected results. It can be seen that it experiences a drop in the plot before resuming a rise in trend. This could be caused by an error in the system, or a defect in the material, arising either from manufacture or an initial crack in the microstructure of the carbon fiber pipe.

Comparing results from the compression tests in both directions show that like most composite materials, they exhibit anisotropic nature. This can be seen in Figure 6. The transverse compression test results were plotted against the secondary y-axis, while the longitudinal results were plotted against the primary y-axis. A significant factor affecting this drop in values is that the transverse compression test was also a test on the structure as well as on the material. This is because in the longitudinal direction, the area acted upon was on the thickness of the pipe unlike in the transverse direction which had a hollow structure. Values gotten in the transverse direction are specific to the structure and if conducted on a rod, higher values of stress will be expected. However, the values of stress and load will be lower than those in the longitudinal direction. Composites generally withstand higher loads if experienced along the length of the fiber arrangement and this can be confirmed when comparing the load displacement values in Figure 6. The results from this study are in agreement with that of Rosso (2006) despite the fact that two different composites were used for the present study. According to Rosso (2006), ceramics are known for their high strength, stiffness and ability to withstand high temperatures. However, they are also very brittle in nature and this is one of the reasons why ceramic matrix composites are aimed at increasing toughness. In Rosso's study, increased ceramics toughness was achieved by reinforcement with fibers or particulates. An increase in toughness was observed in the particulate reinforced ceramic and an even higher difference in fiber reinforced ceramic. Unlike the monolithic and particulate reinforced ceramic, the fiber reinforced ceramic did not undergo brittle failure but instead continues to exhibit its load bearing capacity proving the existence of excellent toughness or ability to plastically deform before fracture

Conclusion

Mechanical tests conducted on pipes can reflect real life situations faced by pipes during application in the field. Hence, different testing methods such as compression, tensile and shear tests become important. From the test conducted, it can be concluded that the results and behaviour expected from a composite material under compression were achieved. No composite pipe deformed plastically and withstood high loads and stress. In general, the Young's modulus of unidirectional carbon fibre reinforced plastics ranges from 130Gpa to 200Gpa. However, values calculated in this test are within 32Gpa and 46Gpa. To further understand the characteristic material properties of composite pipes, the use of strain gauges can help in the proper approximation of Young's modulus, Poisson's ratio, and the stiffness of the pipe because of its accuracy. Also, tensile tests as well as shear tests can be conducted on composite pipes. To further understand the behaviour of composites under shear and tension. Furthermore, several types of composite pipes should be tested upon to compare results and properties of the various composite materials and to understand the best applications for them as this study has shown the need for proactive testing of composites prior to been deployed to the field.

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