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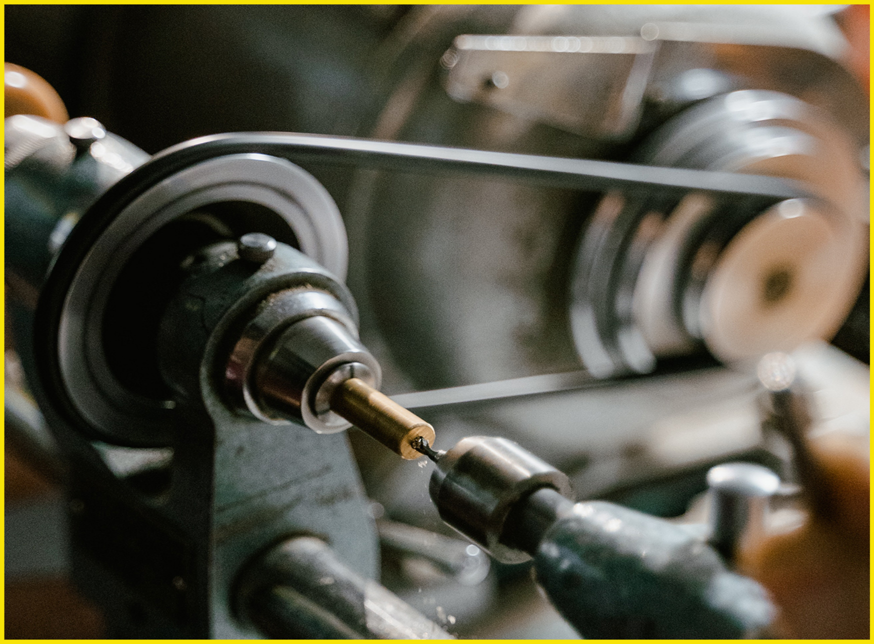

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- Engineering Tribology
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CONTENT

Editorial

The vision of the Editorial Board of the journal of the Nigerian Institution of Mechanical Engineers (**NIMechE**) is to establish a learned journal that is recognized internationally for its high academic scholarship and practical applications of mechanical Engineering science. Our mission is to frequently publish articles that are well researched, original and of high quality from the academia and the industry. In order to ensure that we meet our quality standard, we have carefully chosen some outstanding Mechanical Engineers as Editorial Board and regional factors. All the members of the board are engineers who are very knowledgeable in the areas of professional practice.

This Edition of the journals contains 5 high quality papers in the areas o Machining, Renewable energy systems and composite materials.

The board is grateful to the contributors, members of the Editorials board and the secretariat staff or their cooperation and support in making the publication of the journal possible.

Engr. Prof. Aniekang Offiong ***FNIMechE***

EDITOR IN CHIEF

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OPTIMISATION OF PLASMA ARC CUTTING PROCESS OF AISI 304 STAINLESS STEEL USING DESIGN OF EXPERIMENT

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ABSTRACT:

Owing to its corrosion resistance capability, stainless steel stands out as a material of choice in food processing and other allied industries. However, cutting, during manufacturing activities, poses enormous challenge with regular thermal cutting processes. This study has optimized plasma arc cutting process of AISI 304 stainless steel using a full factorial experimental design. The input process parameters were Cutting Speed (CS), Cutting Current (CC) and Gas Pressure (GP) while the response variables were Material Removal Rate (MRR) and surface roughness. Analysis of Variance (ANOVA) was performed in order to identify the effect of each input process parameters on the response variables. ANOVA revealed that whereas CS made 31.1% contribution to surface roughness of the stainless steel, CC and GP only contributed as much as 31.7% and 28.2% respectively. CC had the most significant effect of 36.07% on MRR followed by GP and CS with 28.02% and 27.11% respectively. While the optimal cutting conditions for surface roughness were found to be 4000 mm/m for CS, 80 A for CC and 6 bar for GP, the optimal values for MRR were 4000 mm/m, 60 A and 6 bar for SC, CC and GP respectively. It can, therefore, be concluded that increase in cutting current favours increased material removal rate during plasma arc cutting processes of AISI 304 stainless steel.

KEYWORDS: Cutting speed, Cutting current, Gas pressure, Material removal rate, Surface roughness

1.0 INTRODUCTION

The need to cut thicker sections with affordable and less energy has given rise to the thermal cutting process which has found application in various fields such as construction, aerospace, shipping and other industries. Thermal cutting process is considered most suitable for cutting metals of different material types and sizes (Kolhe et al, 2018). Plasma arc cutting (PAC) is one of the flame cutting processes which use the extremely constricted ionizing stream of gas to cut any tough metals (Bidajwala et al, 2015). This technology has to be well understood and deployed for metal cutting because of its advantages over other cutting methods (Cinar et al 2018). Metals like aluminium and stainless steel form an oxide that inhibits further oxidization, thereby, making conventional oxy-fuel cutting impracticable. Plasma cutting, however, does not rely on oxidation to work, and thus can cut aluminium, stainless steel and any other conductive material (Salonitis and Vatousianos, 2012). Bogdan et al (2013) reported that plasma cutting is an unconventional cutting technology that has almost the best relation between cost and quality value for money. In addition, the processing speed is far greater than the technology of conventional machining, and its quality is comparable to the laser cutting technology.

Surface finish is a very important output parameter in any machining process. It plays an important role for the tribological operation of any component. Ghany & Newishy (2005), in agreement with Thawari et al (2003), predicted that surface roughness reduces as cutting speed increases with reduced frequency, laser power and gas pressure. This output parameter is also improved by high laser power and lower feed rate (Rajaram and Zaleski, 2004). In order to reduce surface roughness to the barest minimum. Madic and Radovanov (2012), in a study, suggested a cutting speed 7 m/min and gas pressure of 3 bar, while laser power should be kept at an intermediate level of 0.9 kW. Qianhong et al (2008) investigated arc current and mass flow rate on the plasma cutting arc. It was discovered that longer nozzle favours reduced temperature in the torch. The reason is that the radiation is assumed to be directly proportional to pressure (Ghorui, and Previtali, 2016). and the pressure in the torch increases with nozzle length as a result of nozzle chocking. Chamber pressure is also said to be affected by the length of the nozzle.

In another study, Salonitis & Vatousianos (2012) monitored the quality of cut using plasma arc cutting process by measuring conicity of the geometry, surface roughness and size of the heat-affected zone (HAZ) using cutting speed, cutting current, gas pressure and cutting height as input parameters. They found that surface roughness and conicity are principally affected by the cutting height while HAZ is affected by cutting current in agreement with Salons et al [12]. The inefficiency and ineffectiveness associated with conventional methods of machining that involve close contact and hence inevitable tool wear and material wastage prompted Cinar et al (2018) to develop PAC process using same process parameters as Salonitis & Vatousianos (2012). Their quality characteristics were surface finish and metallurgical effects of the cut. Reduced number of experiments was advocated in their conclusion in order to cut cost. This made them prefer the use of design of experiment (DoE) to sufficiently estimate the main effect of the key parameters.

While agreeing with earlier researchers on machining being the most adequate process to achieve desirable shapes and sizes and getting rid of burrs, Aezhisai Vallavi et al (2015) identified cutting forces as a major factor in machining processes. Having reviewed many works, they concluded that cutting speed ranks high among process parameters that can affect cutting force in machining operations. In their final submission, they argued that even though cutting forces can be predicted experimentally and analytically, it decreases with considerable increase in cutting speed. This position is in tandem with that of Adedayo et al (2015) who also concluded that rate of cutting, which increases with cutting pressure, is also decreased with carbon content of the steel material.

For general full factorial designs, ANOVA shows which factors are significant and regression analysis provides the coefficients for the prediction equations (Adedayo et al (2015) . When the number of factors, level of factors and replicate of the experiment are too high, the costliest experimental resources are encountered. The fact that the sample size grows in the number of factors and levels of factors makes full factorial designs too expensive to run for the purpose of experiment. This informed our choice of only three process parameters and two output parameters. This design allows for analyses of responses measured at all combinations of the experimental factor levels (Kaya, 2016). In many applied research work, it is used to answer questions such as which factors has the most influence on the response and possible interactions between two or more factors that influence the response? By examining the multiple variables, we get more accurate results of other real life examples (Adedayo et al (2015).

This study optimizes plasma arc cutting process of AISI 304 stainless steel using a full factorial experimental design while measuring individual and combined effects of process parameters on the responses variables. Conclusions were drawn from the analysis of variance performed on all the input parameters.

2.0 MATERIALS AND METHODS

2.1 Materials

The materials used for the machining processes include AISI 304 stainless steel, surface roughness tester (SRT-620), weighing machine, stopwatch and CNC Gantry Cutting Machine (CNC-3000).

2.2 Design of Experiment

DoE was utilized in accordance with full factorial $L_{27}(3)^3$ design technique using Minitab 17 statistical software to obtain the best combination of design factors to achieve the optimum performance measures. This technique is suitable for experiments with two or more factors, each with discrete levels, and whose experimental units take on all possible combinations of these levels across all factors. The desired responses in this study are material removal rate, and surface roughness which have been identified to be heavily affected by the three cutting variables highlighted. The factor levels of input variables are shown in Table 1 while the experimental design layout is shown in Table 2.

2.3 Machining Process

Cutting operation was carried on gantry plasma cutting machine (model: CNC SG3000, maximum speed: 12000 mm/min, maximum cutting thickness: 80 mm). (20×15×80) mm specimens was cut using oxygen and air as plasma gas and shielding gas respectively for all 27 runs of experiments to investigate the surface roughness of cut.

Table 1: Factor Levels of Machining Variables

Factors	Unit	Level 1 (−)	Level 2 (0)	Level 3 (+)
Cutting Speed	mm/min	3000	3500	4000
Cutting Current	A	60	70	80
Gas Pressure	bar	4	5	6

Table 2: $L_{27}(3)^3$ Experimental Design Layout

Run Order	Cutting speed (mm/min)	Cutting Current (A)	Gas Pressure (bar)
1	3500	60	6
2	3000	70	4
3	4000	70	5
4	3000	80	5
5	3500	70	5
6	3000	60	4
7	3000	60	5
8	4000	60	4
9	4000	60	5
10	4000	80	4
11	3000	80	4
12	4000	70	4
13	4000	70	6
14	3500	80	6
15	3500	80	4
16	4000	60	6
17	4000	80	5
18	3000	70	5
19	3000	60	6
20	3000	70	6
21	3500	60	4
22	3500	70	4
23	3500	70	6
24	3000	80	6
25	3500	60	5
26	3500	80	5
27	4000	80	6

2.4 Measurement of Surface Roughness

Surface roughness measurement was obtained using SRT-6200 surface roughness tester to measure the surface roughness of the cut. The average of five separate measurements taken along the midpoint of the specimens was recorded as the surface roughness as displayed on the LCD on the device.

2.5 Measurement of Material Removal Rate

The MRR was measured by taking the difference in weight of the specimens before and after cutting; then dividing it by the amount of time spent the cutting operation. A weighing scale was used to measure the weight of the specimens before and after curing.

3.0 RESULTS AND DISCUSSION

3.1 Experimental Results of S/N Ratios

Table 4.1 shows the values for the experimental result obtained during the plasma arc cutting of the specimens and their corresponding S/N ratio for responses. It indicates how the process parameters affect output parameters in the CNC plasma machine. It can be observed that at higher cutting speed and current, material removal rate increases and this can be attributed to the energy exerted on the cut surface. The amount of time the flame stays on the surface of cut material as well as increase in the cutting current resulted in increase in MRR. S/N ratios of individual responses were calculated using Equations 1 and 2.

. Smaller-the-better

$$S/N = -10\log\frac{1}{n}\left(\sum_{i=1}^{n} y_i^2\right) \quad (1)$$

Larger-the-better

$$S/N = -10\log\frac{1}{n}\left(\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \quad (2)$$

where S/N is signal to noise ratio, n is the number of repetitions in a trial and y is the measure quality characteristic for the ith repetition.

The increase in arc current moves the torch away from the cutting surface. This causes the flame to blow onto the material from a higher point and to spread across the material surface. Therefore, surface roughness, kerf width and hardness on the cutting surface are increased.

(1)

Table 3: Experimental Results and Signal-to-Noise Ratio Values

Run Order	CS (mm/min)	CC (A)	GP (bar)	Material Removed	Time Taken to Cut (s)	MRR (g/sec)	S/N for MRR (dB)	Surface Roughness (μm)	S/N for SR (dB)
1	3500	60	6	23	10.57	2.18	6.75	0.77	2.33
2	3000	70	4	20	11.07	1.81	5.14	1.72	-4.71
3	4000	70	5	24	9.38	2.56	8.16	1.19	-1.52
4	3000	80	5	22	11.06	1.99	5.97	1.01	-0.07
5	3500	70	5	7	10.28	0.68	-3.34	1.25	-1.9
6	4000	60	4	31	9.48	3.27	10.29	1.78	-4.98

7	3000	60	5	21	10.16	2.07	6.31	0.98	0.21
8	3000	60	4	17	8.58	1.98	5.94	2.57	-8.18
9	4000	60	5	21	8.98	2.34	7.38	0.44	7.07
10	4000	80	4	10	9.69	1.03	0.27	1.51	-3.58
11	3000	80	4	14	9.31	1.5	3.54	0.58	4.72
12	4000	70	4	10	9.95	1.01	0.04	0.79	2.05
13	4000	70	6	19	12.79	1.49	3.44	1.35	-2.62
14	3500	80	6	18	10.41	1.73	4.76	3.1	-9.83
15	3500	80	4	21	10.47	2.01	6.05	0.3	10.46
16	4000	60	6	18	8.71	4.14	6.31	1.7	-4.58
17	4000	80	5	22	9.1	2.42	7.67	2.32	-7.31
18	3000	70	5	11	9.82	1.12	0.99	0.22	6.45
19	3000	60	6	28	12.22	2.29	7.2	0.55	5.15
20	3000	70	6	24	11.01	2.18	6.77	0.41	7.74
21	3500	60	4	12	10.01	1.2	1.57	0.96	0.35
22	3500	70	4	19	8.94	2.13	6.55	1.44	-3.18
23	3500	70	6	19	8.54	2.22	6.95	0.86	1.33
24	3000	80	6	18	10.01	1.8	5.1	1.61	-4.11
25	3500	60	5	20	10.21	1.96	5.84	1.71	-4.65
26	3500	80	5	20	8.72	2.29	7.21	1.4	-2.95
27	4000	80	6	18	9.22	1.95	5.81	1.64	-4.31

3.2 Analysis of Variance (ANOVA)

The ANOVA is applied to study the significant effect of the experimental factors under 95% confidence level and significant level of 5%. The degree of freedom (DoF), sum of square (SS), mean square values (MS), f-value and percentage contribution (p) for the responses are tabulated in Tables 4 and 5.

The ANOVA for surface roughness shown in Table 4 shows a percentage error of 8.98% with cutting current contributing up to 31.8% signifying the most significant parameter followed by cutting speed with 31.1% contribution in agreement with findings of Aezhisai Vallavi et al [13] and Salonitis & Vatousianos [4]. Gas pressure has the least contribution with 28.1%. This goes to show that the three process parameters have significant effect on surface roughness of the specimen.

Table 4: ANOVA for Surface Roughness

Ractor	DoF	SS	MS	F	P (%)
CS	2	3.8052	1.9026	34.6904	31.14496672
CC	2	3.8828	1.9414	35.3978	31.78011058
GP	2	3.4328	1.7164	31.2953	28.09693097
Error	20	1.0969045	0.05485		8.977991733

Total	26	12.2177045	0.46991		100

Table 5 shows that the cutting current has the highest impact (36.08%). When the cutting speed was increased above a safe threshold, the cutting torch moved too fast for the plasma arc to maintain stability. Therefore, the plasma arc cannot remain perpendicular to the cutting front thereby resulting in the formation of drag-lines on the cutting surface. In the same vein, wavy surface and drag-lines also results from over melting of the processing area as a result of too low cutting speed.

Table 5: ANOVA for Material Removal Rate

Factor	DOF	SS	MS	F	P (%)
CS	2	2.2329	1.11645	34.9653	27.92974
CC	2	2.8842	1.4421	45.1641	36.07638
GP	2	2.239	1.1195	35.0608	28.00604
Error	20	0.638605	0.03193		7.987849
Total	26	7.994705	0.30749		100

With increased cutting current, material removal rate increased as a result of extra current which exerted more energy and increased the temperature on the material during cutting. This favoured faster removal of material. Gas pressure was the second most significant parameter on the material removal rate having contributed 28%. MRR increased as a result of excessive pressure which gave cooling effect rather than blowing the molten material from the heated zone. Incomplete removal of material may also occur with too high speed. These results indicated the level of correlation between the reference sequence and the obtained sequence. Therefore, the optimal levels of the process parameters are indicated by the highest levels of the *means* of levels for different parameters.

The effects of all the factors are significant since their individual p-values are greater than 0.05%. Certain experimental noise in were responsible for R-sq being less than 80%. However, the experimental R-sq is greater than the adjusted for the two responses, showing that the experimental noise have been taken care of.

3.3 Empirical Model for Optimization of Quality Characteristics

In order to optimize the response parameters, Minitab 17 software was used to generate an empirical model equation as shown in Equations 3 and 4 and to specify the R-sq value for the two response parameter as shown in Tables 4.2 and 4.3. The optimal values obtained from the analysis of variance as shown in Tables 4 and 5. The main effect plots of the signal-to-noise ratio shown in Fig. 1 and Fig. 2 were used to determine the optimum values for each process parameter during the cutting procedures.

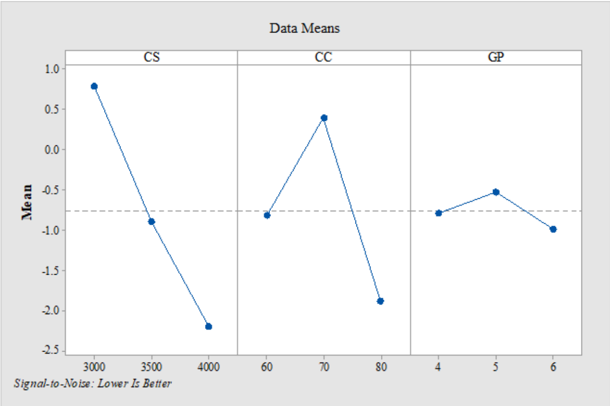

Fig. 1: Main Effect Plot for Surface Roughness

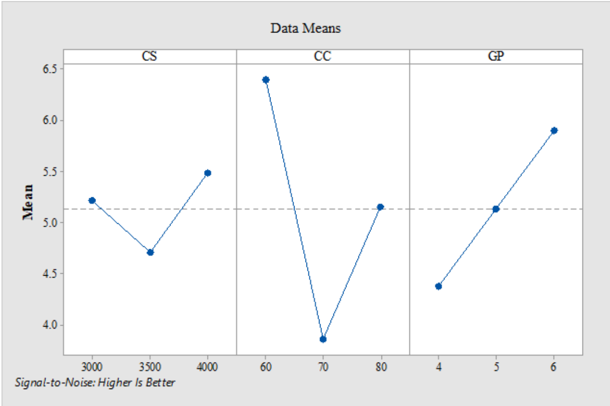

Fig. 2: Main Effect Plot for Material Removal Rate

For the optimization of the surface roughness and material removal rate, the empirical model Equations 3 and 4 are used;

$$Surface\ Roughness\ (\mu m) = 14.0 - 0.003CS - 0.054CC - 1.0GP \quad (3)$$

R-sq = 66.31% and R-sq (adjusted) = 50.56%

$$Material\ Removal\ Rate\ (g/sec) = 4.75 + 0.0027CS - 0.0523CC + 7.61GP \quad (4)$$

R-sq = 63.36% and R-sq = (adjusted) = 57.34%

It is observed from the equations that an increase in all the parameters will cause a corresponding decrease in the surface roughness (Equation 3), while a decrease in cutting current will amount to a further increase in the MRR. This also agrees with earlier works by Kolhe et al [1] who investigated quality of cutting of mild steel.

3.4 3D Surface Plots of Output Vs Most Significant Process Parameters

The 3D surface plots of surface roughness and material removal rate are illustrated in Fig. 3 and 4. The plots give an idea of how any change in cutting speed and cutting current affect the surface roughness and material removal rate when the gas pressure is kept constant. The plots also indicate that as cutting current increases, cutting speed decreases and vice versa.

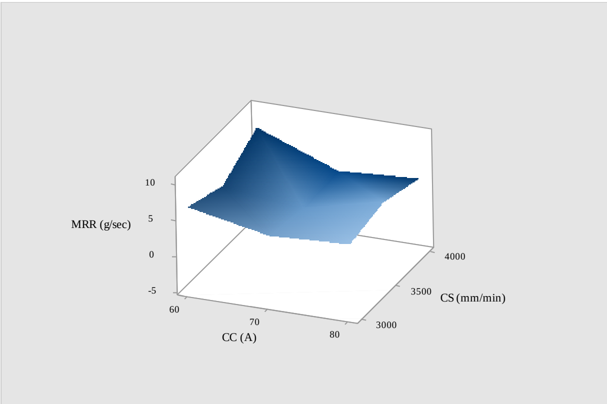

Fig. 3: 3D Surface Plot for Surface Roughness

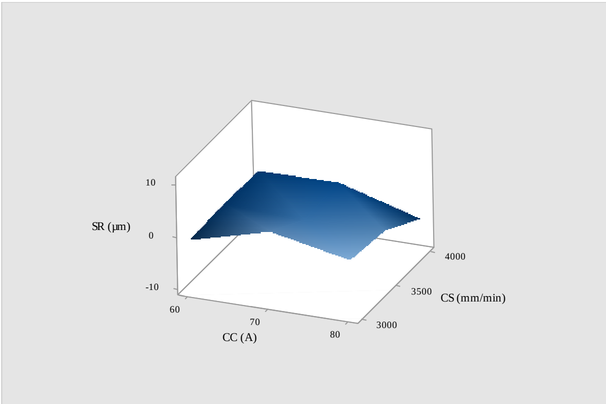

Fig. 4: 3D Surface Plot for Material Removal Rate

4.0 CONCLUSION

The results presented in this study indicated that quality of the cut using PAC is determined by a number of factors among which include cutting speed, gas pressure and cutting current. It also showed that the effect of process parameters of PAC on surface roughness and material removal rate of AISI 304 stainless steel can be successfully investigated using full factorial experimental design for different industrial applications. Cutting speed and current as well as gas pressure were found to contribute significantly to surface finish and the rate at which materials are removed during machining process. While cutting current had the most significant effect on both surface roughness and material removal rate with 31.7% and 36% contributions respectively, gas pressure contributed the least of 28% to surface roughness and cutting speed dropped back the most for material removal rate as shown by analysis of variance. The main effect plots showed that optimal material removal rate in achievable with 4000 mm/min cutting speed, 60 A cutting current and gas pressure of 6 bar while the optimal surface roughness will be attainable with the same parameters but cutting current adjusted to 80 A.

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LUBRICANT CONDITION MONITORING – A STEP TO PROACTIVE AND PREDICTIVE MAINTENANCE

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ABSTRACT:

Lubricant condition monitoring is an important aspect of proactive and predictive maintenance philosophy. It is a tool which can be used not only to guarantee the lubricant condition to fulfil its function, but also to monitor the health of industrial machines so as to make timely, useful maintenance, equipment utilization decisions, with minimal risk, and thus conserve investment. This work demonstrates the use of statistical evaluations to set limits on the concentration of wear metals and the determination oil degradation quantitatively (additive depletion) in oil samples extracted from mechanical equipment, and to give expert advice as regards the state of the equipment. The case studies considered were a CAT 330D – Engine and a Perkins Plant Generator. Data normalization for the CAT engine was done at 500hrs; cautionary and critical limits of wear determined; and the effects of the high iron and soot observed was analyzed. For the Perkins generator, high calcium ingress was observed which was as a result of water ingress into the engine.

KEYWORDS: Lubricant Condition Monitoring; Original Equipment Manufacturer (OEM); Normalization; Additive; Depletion; and Limits

1.0 INTRODUCTION

Condition monitoring is a maintenance philosophy that involves periodic measurement of the mechanical and process parameters that govern the performance of a machine in order to gain a relative indication of the mechanical state of the machine. It provides a means for observing the health of equipment and the identification of problems before component or machine failure occurs.

Condition monitoring techniques include lubricant condition monitoring, vibration monitoring, thermography, ultra-sonic, ferrography and radiography.

Unscheduled equipment downtime as a result of catastrophic failure which is normally accompanied by a breakdown maintenance approach leads to loss of production time, and reduced return on investment (James, 1992). In the past, this approach to maintenance was widely practiced and production suffered. Today, however, with the sophistication and complexities of industrial processes and machinery, together with the current cost of equipment, labor and production, breakdown maintenance is no longer a totally viable option. Preventive maintenance however evolved to replace breakdown maintenance as it was found that breakdown maintenance was not the best way to look after most pieces of machinery in industry (Macian, et al., 2003). Preventive maintenance involves the servicing, overhaul and replacement of items of plant based on a scheduled time interval such as operating hours/kilometers, or on a calendar basis (Yuegang, 2017). This was certainly a step in the right direction but it meant that units which did not require maintenance were fixed anyway. These caused problems as pieces of normally operating equipment were disturbed resulting also in a waste of financial resources and production time. In view of the foregoing, the question arises as to when, how and what particular mechanical component(s) should be maintained or replaced in a functioning mechanical system so as to minimize cost, increase return on investment and prolong the life of mechanical systems by forestalling catastrophic failure, and if possible, push the frontiers of specification beyond the limits established by the original equipment manufacturer. Thus, the aim of this work is to demonstrate how Lubricant Condition Monitoring can provide a means of obtaining answers to these pertinent questions. Also, as a diagnostic tool, it would ascertain the health of industrial machines with respect to the serviceability of the lubricant employed, rate of additive depletion and the wear characteristic of the equipment. It is hoped that such knowledge would contribute to, and improve, maintenance practices in indigenous industries.

1.1 Lubricant Condition Monitoring

This technique involves the removal of a small sample of oil from an operating piece of machinery (Macian, et al., 2003). The oil is subjected to a number of physical and chemical tests that determine the performance status of the machine and the oil, additive content, depletion and the level of contaminants in the oil as well as the serviceability of the oil.

Just as samples of blood can be extracted and examined to identify the health condition of an individual, samples of lubricating oil circulating within a machine can also be indicative of the health of the machine. This is because, lubricant inspection and testing can help diagnose the internal condition of oil-wetted components. It also provides valuable information about the lubricant serviceability since lubricating oil carries with it, evidence of faults from different positions within the machine to some point where a sample could be extracted. Thus, wear rate and level of the machine can be determined, and the particular member undergoing wear identified.

1.2 Lubricant Condition Monitoring Parameters

According to Ashley (2006), a normal test programme would include:

i. Elemental analysis
ii. Particulate Analysis (normally quantification only)
iii. Viscosity measurement
iv. Contamination (water, fuel, glycol)

Usually, these parameters are grouped into two broad categories, namely: oil contamination parameters, and oil degradation parameters (Yueghang, 2014). Contaminants in lubricating oils are particles, compounds or elements, solid or fluid, foreign to a lubricating oil sample whose composition has become different from the manufacturer's stock (Abel, 2003). Contaminants can include wear elements from oil wetted machine parts, dust, water, glycol, fuel and soot. There are a number of techniques and instruments available for contaminant detection and quantification, such as spectroscopy (commonly Atomic Emission Spectrometer), ferrography, flash point apparatus for fuel detection and Karl Fischer titration for water.

Oil contamination precipitates oil degradation. Since additives are added to lubricating oil base stock to enhance its lubrication properties, increase its life span and its area of application such as protection from high temperatures, pressures and long hours of use, additive depletion and viscosity - related ones are parameters of oil degradation (Yueghang, 2014). Viscosity may be considered the most important physical property of a lubricant, particularly in hydrodynamic and elastohydrodymic lubrication applications, because it determines the lubricant load carrying ability as well as its ability to flow through a lubricant system (Yuegang, 2017). It also provides early warning of lubricant degradation and/or contamination. Viscosity increase may be attributed (Yasuhiro, 2011) to solid contamination, improper top-off oil grade, overheating, coolant/water contamination, or oxidation. On the other hand, viscosity decrease could be due to fuel contamination, improper top-off oil grade, or additive degradation. Concurrent occurrences of overheating and fuel dilution could have little effect upon overall viscosity levels, so it is important that other information from spectroscopy be taken into account.

2.0 RESEARCH METHODOLOGY

The critical factor in oil analysis is the interpretation of the oil analysis result. According to Macian, et al., (2006), the oil analysis interpretation includes discussion of the equipment wear state, level of oil contamination, oil condition and a recommendation outlining any corrective actions that are necessary. The aim is to produce a concise summary of the engine and oil condition. There seems to be a consensus among researchers on the range of factors to be considered when interpreting oil analysis results. Such factors include; equipment manufacturer wear limits, oil baselines obtained from a blank, engine age, engine metallurgy, environmental condition, type of service, oil drain interval, and oil consumption (John, 1997; Macian, et al., 2003).

The use of OEM wear limits is not an effective means of determining the performance state of a component. According to John (1997), the wear limit tables produced by OEM, though based on extensive research and testing by those who manufactured the equipment and know the equipment best, at the end of the day, reflect average situations and are to be used as a guideline only. Machines rarely work in average situations and often limits determined in a certain environment can have little relevance in other environments, particularly in Africa, where very few equipment are manufactured. What seems possible for Japan, Western Europe or North America might not seem possible for South Africa or Nigeria (John, 1997).

It is thus far more beneficial to assess the state of a machine or lubricant on the basis of a trend analysis. Establishing a trend will give an early alert so that corrective action can be taken to prevent a major failure (Abel, 2003). A trend is a regularly scheduled set of samples over a span of time. It is a unique history of what is happening to a unit within its specific application. The trend observed from a series of samples taken at regular time intervals from the same engine have a much higher diagnostic value than the results from a lone sample compared with OEM specifications (Ashley, 2010).

In addition to trend analysis, the results of oil analysis must also be studied holistically (Amin, 2014). In other words, one must look at the whole picture. Only by viewing the readings simultaneously can a proper diagnosis be obtained. It is important to remember that an elevated reading can be caused by more than one reason at a time. John (1997) noted that trending and viewing results in a holistic manner offers positive benefits for any type of condition monitoring technique, not just oil analysis.

2.1 Normalization

Drawing conclusions from the absolute values of wear readings returned from the laboratory, without considering the period the oil has been in service, can be very misleading and even meaningless.

Assuming that oil consumption remained fairly constant, a useful formula to normalize for time is expressed in equation (1) (Ashley, 2010):

$$R_N = \frac{R}{t} \times T \qquad \text{.......... 1}$$

where

R_N is the normalised value of a reading,

R is the original laboratory reading?

t is the period the oil has been in use (kilometres, hours or months in the case of industrial equipment), and

T is the parameter being used to normalise R, often 15 000 kilometres, 250 or 500 hours or months (the same units as t).

When oil consumption must be accounted for, the following equation for the compensated wear rate in *mg/h* as derived by Macian, et al., (2003) can be employed

In analyzing Atomic Emission Spectroscopy (AES) data, it is important to have a good knowledge of the machine metallurgy, and the chemical composition of the lubricating oil base stock as well as any additives that may be present so the data can be related back to the wear of a specific component, or to the ingress of specific contaminants (Yasuhiro, 2011). In addition to having a good knowledge of the chemical composition of the additive packages, it is also important to know the expected concentrations of the different metal-containing additives in the oil. To do this, new oils should be baseline on an annual basis, or whenever a change in oil type or formulation is suspected (Ashley, 2006). By comparing the elemental fingerprint of the new oil baseline to the used oil sample, problems such as additive depletion or the addition of wrong oil can be quickly and easily diagnosed. Care should be taken, when looking at additive elements since additive depletion does not necessarily cause a drop in additive element concentration, as measured by AES (Macian, et al., 2006).

to normalize the laboratory readings for oil consumption:

$$C(t) = \frac{\beta + \dot{m}A\dot{r}\,C_a}{(\dot{m}Ar - \dot{m}Av)} \cdot \left[1 - e^{-\left(\frac{\dot{m}Ar - \dot{m}Av}{mA(0)}\right).t}\right] + C_o . e^{-\left(\frac{\dot{m}Ar - \dot{m}Av}{mA(0)}\right).t} \quad (2)$$

where

$mA(0)$ is initial oil mass (kg)

C_o is initial contaminant concentration (ppm)

$\dot{m}Av$ is *volatile* oil consumption rate (kg/h),

$\dot{m}Ar$ is fresh oil refills rate (kg/h),

C_a is additive concentration in fresh oil (ppm), and

β is wear rate (mg/h).

2.2 Establishing Limits

In lubricant condition monitoring, some pertinent and logical questions to ask include, "What levels of wear and additive depletion are normal and abnormal?" or "What wear limits should be used?" and "How much viscosity increase is acceptable?" In other words, "What limits should be imposed on the trends observed?" As in many other technologies, limits are devices used in oil analysis, to alert the user to abnormal, or potentially abnormal, situations. Typically, there are two levels of limits: **Cautionary** and **Critical**. According to Ashley (2010), when a cautionary limit has been exceeded, it means the parameter must be monitored closely, and when a critical limit is exceeded it means immediate action must be taken. Three consecutive instances of a parameter exceeding a cautionary limit should be treated as if the critical limit had been exceeded. Limits can be set on the high side, the lo,w side or, in some cases, both. High-end limits would be applied to tests like wear metals and contaminant readings, low end limits to tests like the total base number (TBN) or additive levels, and both to tests like viscosity which can go either way.

The *cautionary limit* would be defined as presented in Equation 3 while *critical limit* is presented in Equation 4 (Ashley, 2010):

$$L_a = \bar{x} + \sigma \quad (3)$$

where

L_a is the cautionary limit,

$\bar{x}$ is the mean, and

σ is the standard deviation.

$$L_c = \bar{x} + 2\sigma \quad (4)$$

where L_c is the critical limit.

$$\bar{x} = \frac{\sum x}{n} \quad (5)$$

$$\sigma = \sqrt{\frac{\sum(x - \bar{x})^2}{n}} \quad (6)$$

where n is the total number of samples

For fluid degradation and contamination, limits should be based upon past analysis of machine wear as a function of the contamination or degradation (John, 1997). Especially as far as contamination goes, different contaminants are going to affect wear differently; for example, diamond ore is far more abrasive than dust found in a flour mill environment. Ashley (2010), noted that the relationship between wear and contamination is exponential, and only experience can determine the levels of contamination that start to generate unacceptable wear.

3.0 RESULTS AND DISCUSSION

3.1 Case Studies - CAT 330D-Engine

The following case study illustrates the process of normalization for time, and the use of statistics in establishing limits for the particular units in their specific application. The analysis is done on the assumption that oil consumption rate is negligible. A record of the Oil hours in addition to the Service meter unit (SMU) or equipment hours is available. Based on the results presented in Table 1, it can be observed that, for all the samples analyzed, the oil hours are not consistent; neither is the SMU intervals.

Table 1: Oil analysis Laboratory Result for CAT 330D-Engine

Sample No.	Smu	Oil Hrs	Cu	Fe	Cr	Al	Pb	Sn	Si	Na	Ca	Mg	Zn	P	Soot	Sulphate	Water	Fuel	V 100
1	6172	362	1	13	1	3	1	1	6	1	2829	333	1605	1350	72	13	N	N	13.2
2	6320	510	0	23	1	4	0	1	5	1	2527	304	1427	1197	78	13	N	N	13.3
3	6678	358	1	46	2	8	1	1	18	2	2752	346	1556	1304	94	13	N	N	13.1
4	6843	523	2	72	3	12	1	2	34	2	2721	347	1521	1276	114	14	N	N	13.4

At 523 oil hours, the normalised Fe reading using Equation 1 above is

$$R_N = \frac{72}{523} \times 500$$

$$= \frac{69ppm}{500hrs}$$

where $500hrs$ is the parameter being used to normalize R .

Similarly, the normalized values for Fe and soot at the different oil hours are given in Table 2:

While Fe shows a steady increase in the normalized value, that for soot was erratic.

Table 2: Normalized laboratory data for CAT 330D-Engine

Sample Number	Smu	Oil Hrs	Fe (ppm)	Soot Index (ppm)	Normalised Fe (ppm/500hrs)	Normalised Soot (ppm/500hrs)
1	6172	362	13	72	18	99
2	6320	510	23	78	23	76
3	6678	358	46	94	64	131
4	6843	523	72	114	69	109

Also, the limits of wear for the iron and soot are determined using statistical means demonstrated below. C*autionary limit* was calculated using Equation 3, *critical limit* using Equation 4, mean using Equation 5, and standard deviation using Equation 6.

For example, from Table 2 for *iron (Fe),*

$$\bar{x} = 43.5 \frac{ppm}{0500hrs}$$

The standard deviation,

$$\sigma = 23.1355$$

The *cautionary limit* is therefore;

$$L_a \cong \frac{67ppm}{500hrs}$$

And the critical limit

$$L_c = 43.5 + 2 \times 3.1355$$

$$L_c \cong \frac{90ppm}{500hrs}$$

Similarly, the mean, standard deviation, cautionary and critical limit for the soot in Table 2 are determined and the result presented in Table 3:

Table 3: Parameter Limits

Parameter	$\overline{x}_{(ppm/500hrs)}$	Σ	$L_{a(ppm/500hrs)}$	$L_{c(ppm/500hrs)}$
Fe	43.5	23.1355	67	90
Soot	103.75	19.7658	124	143

The result of the normalized lab data given in Table 3 shows a steep rise in the amount of Fe and soot for samples 3 and 4 (See Fig.1). The elevated Fe when compared with the Si and Al levels from the raw laboratory result is indicative of dirt ingression. The recommended action was to inspect the air intake system upon which a crack was noticed to have developed inside the air intake tube. Although soot itself is not harmful to diesel engine operation, excessive levels of fuel soot in an oil sample are indicative of inefficient fuel combustion. This is typically due to an incorrect air/fuel ratio as a result of restricted airflow in a filter that results in an insufficient air supply to the combustion chamber or a defective exhaust valve. Inspecting the valves would thus be beneficial.

By comparing Table 1 and Table 2, the value of normalizing for time especially when limits are to be used can be seen.

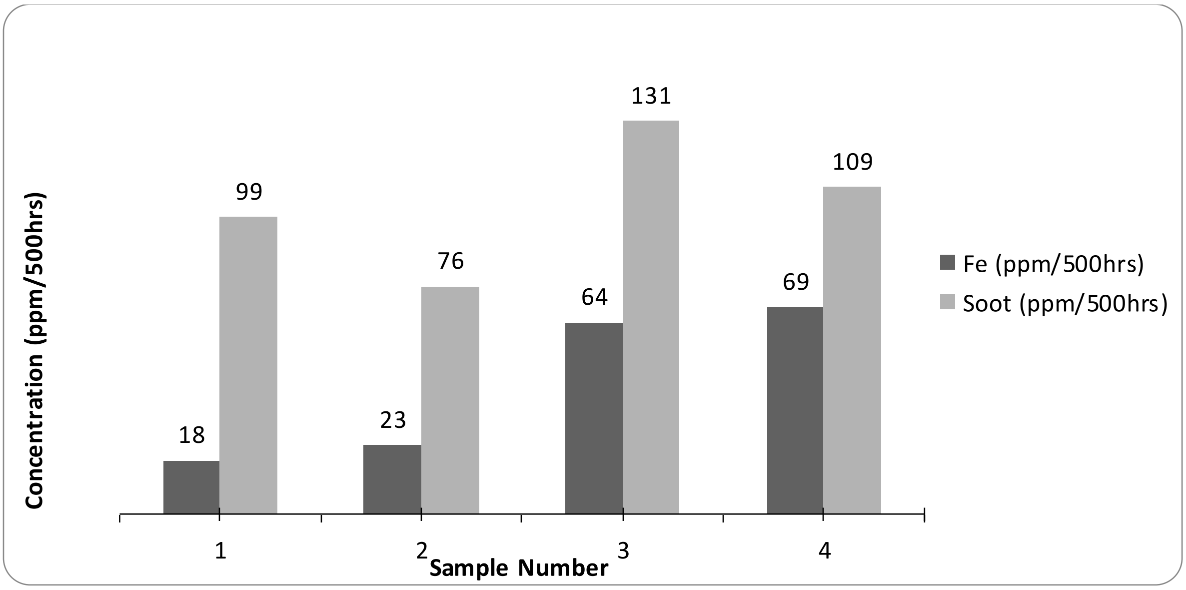

Fig.1: Normalized Lab readings vs. Sample number, CAT 330D-Engine.

3.2 CASE STUDIES - Determination of Additive Depletion: Perkins Plant Generator

Table 4: Seal Laboratory Analysis Report

S/N	PARAMETERS	Zn	Ca
	TEST METHOD / SAMPLE 1.D	ASTM D875-89	ASTM D511-82
1	CONOIL SAE 40 0 HOURS RUN	392 ppm	864 ppm
2	CONOIL SAE 40 50 HOURS RUN	396 ppm	738 ppm
3	CONOIL SAE 40 100 HOURS RUN	306 ppm	1,165 ppm
4	CONOIL SAE 40 250 HOURS RUN	301 ppm	1,539 ppm

Data Interpretation: Remaining Life of ZDDP

The remaining life of zinc dialkyldithiophosphate (ZDDP) can be calculated using Equation 7:

$$\% \text{ of additive remaining} = \frac{\text{ppm of used oil}}{\text{ppm of new}} \qquad ....7$$

From the graph of concentration of Zn in ppm versus degradation time (hours) (See Fig. 2), it is clearly seen that after 100hours there was no noticeable change in the additive concentration. Hence, it can be concluded that the additive has to be considered totally depleted. Therefore, in trying to calculate the remaining percentage of antioxidant in the oil, we have to establish that the percentage of additive in the oil is 100 at 0 hours. Recall;

392ppm ……………….........…0 hours

396ppm …………………..……50 hours

306ppm ………………………100 hours

301ppm ………………………250 hours

Subtracting 300 ppm from each concentration of Zn:

392 ppm – 300 ppm = 92ppm

396 ppm – 300 ppm = 96ppm

306 ppm – 300 ppm = 6ppm

301 ppm – 300 ppm = 1ppm

Let 92 ppm be equivalent to 100%

Then,

$$\frac{96 \times 100\%}{92} = 104.3\%$$

$$\frac{6 \times 100\%}{92} = 6.5\%$$

Again,

$$\frac{1 \times 100\%}{92} = 1.1\%$$

The summary of the results is presented in Table 5

Table 5: Depletion of ZDDP

Zn (ppm)	% Zn	Time (hours)
392	100	0
396	104.3	50
306	6.5	100
301	1.1	250

Table 6: Aging Limits

	CAUTION	CRITICAL
Zinc	-15%	-30%
Calcium	-10%	-20%

From Table 6 above,

δ = standard deviation = -15%;

So 2δ = -30%

Hence cautionary limit for zinc:

Therefore, the mean

$$\bar{x} = \frac{\Sigma F(x)}{\Sigma F} = 348.8ppm$$

Converting to percentage we have:

$$\frac{392 - 348.8}{92} = \frac{100 - y}{100}$$

$\bar{x}$ - δ (first lower limit)

For critical limit

$\bar{x} - 2$ δ (second lower limit):

Giving $y = 53\%$

Hence, first lower limit becomes:

$\bar{x} - 15\% = 53\% - 15\%$

$= 38\%$ *(cautinary limit)*

Second lower limit becomes:

$\bar{x} - 30\% = 53\% - 30\% = 23\%$ *critical limit*

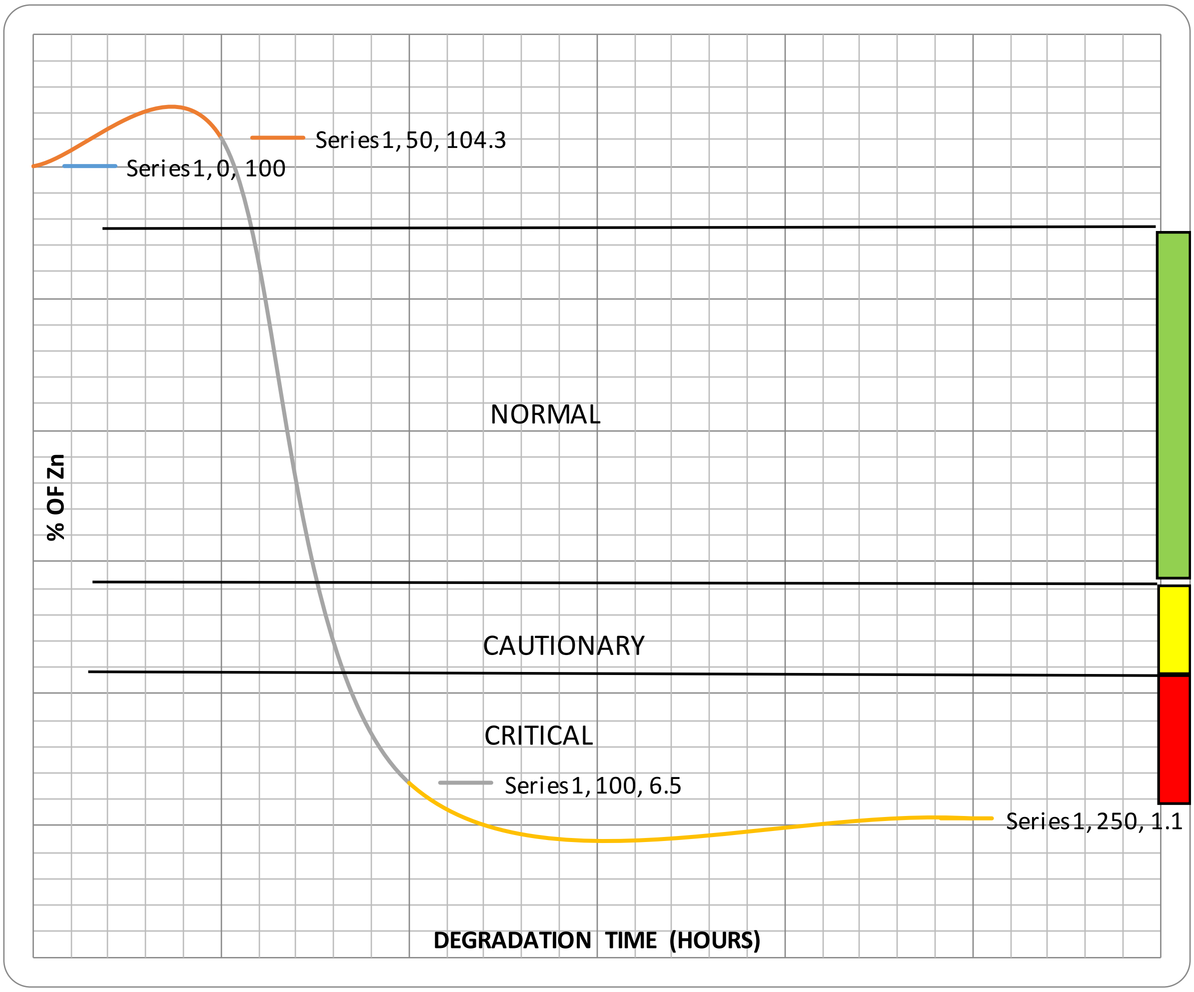

Fig. 2 Alarm Limit

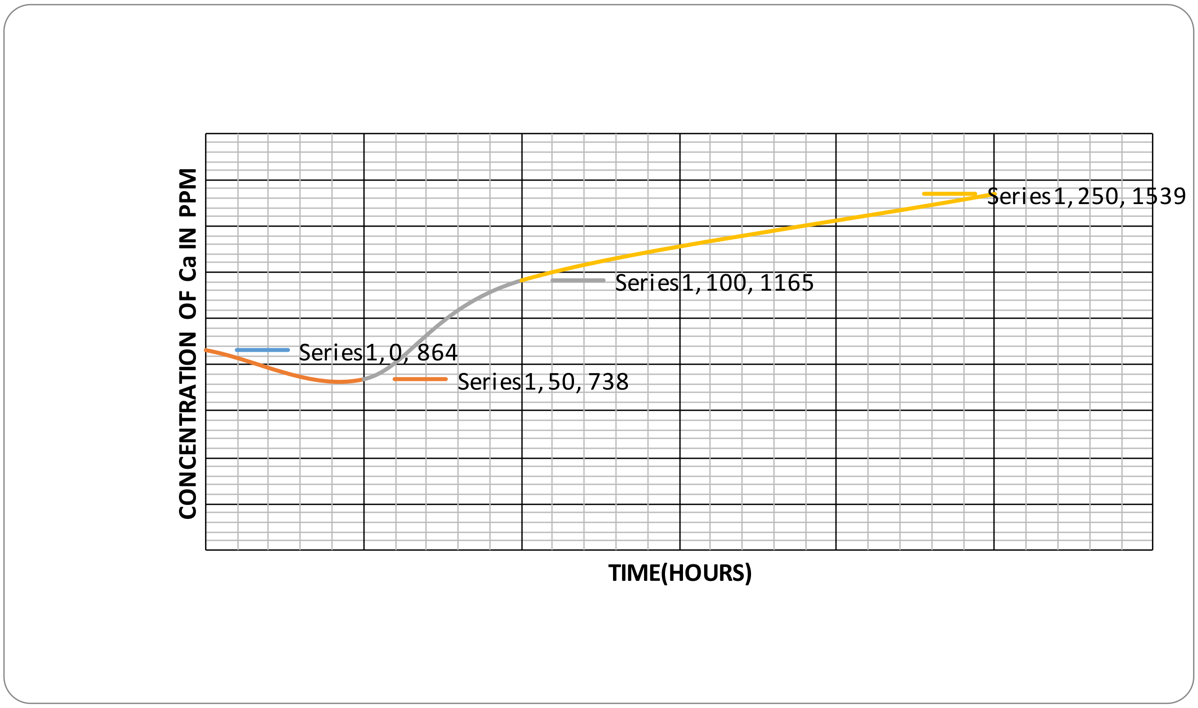

Fig. 3 Depletion of Detergent/Dispersant Additive

From Fig. 3 above, the detergent additive in the lube oil seems to have had an upward trend contrary to the degradation of Zn as shown in Fig. 2. The increase in calcium (Ca) suggests an infiltration in the lube oil which definitely would have caused the rapid depletion of the ZDDP.

From the foregoing, the following recommendations are made:

1. Check oil storage, sampling and handling methods;
2. Bleeding and replacing lube oil with fresh one might be necessary;
3. High calcium level appears to be associated with water contamination and this may also bring about rapid additive depletion;
4. Engine might be over-heating if there is coolant leakage. Consider inspecting the following areas for compromise:

- Water jackets
- Seal(s) or vent and breathers for wear or compromise
- Radiator for leakage.

4.0 CONCLUSION

This work has demonstrated the benefits of lubricant condition monitoring as a guide to monitoring the health of industrial machines and thus improve maintenance practices in organizations by providing a means of adequately maintaining equipment proactively. Also, the use of statistical evaluation in establishing wear limits for metals has been demonstrated. This is a more reliable and efficient way of setting limits as opposed to specifications offered by OEM which are sometimes not available and, even when available, do not take into consideration all the factors affecting wear rate.

Therefore, following the techniques outlined in this work, individuals, industries and organizations can save cost by extending oil drain interval where oil analysis has shown that the oil can still be in use, save cost on unscheduled breakdown and even preventive maintenance, by proactively monitoring the health of machines.

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TOWARDS MODERN MANUFACTURING TECHNOLOGY AND PRACTICE FOR NATIONAL ECONOMIC GROWTH

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ABSTRACT:

In Nigeria today, most segments of the manufacturing sector have collapsed. With a growing workforce of automations, the rules of design are changing. Parts and subassemblies have been designed to take advantage of dexterous labor. This revolutionary change has fundamentally altered global business concepts, practices and procedures. Design for manufacturing is becoming the rule among sophisticated manufacturers. It is the name that has been applied to the good engineering and design principles that govern modern manufacturing in this era of fast tireless, but nevertheless limited production equipment. This paper discusses the challenges and prospects in positioning manufacturing technology and practice for national economic growth, as we approach the third decade of the twenty-first century. It asserts that accurate integration of product design with modern manufacturing methods leads to achieving high quality, low cost and automated production even at early stages of product cycle. This work, therefore suggests that the Nigerian engineers take some time to think of achieving better product design/manufacturing process integration, particularly as it relates to assembly automation and design for manufacturability. The work elucidated that when modern manufacturing technology and practice are employed, there would be significant reduction in manufacturing costs thereby leading to national economic growth.

KEYWORDS: Modern Manufacturing, Manufacturing Technology and Practice, National Economic Growth.

1.0 INTRODUCTION

The important nature of manufacturing industry on economic growth and development serves as a veritable vehicle for the achievement of national economic objectives of employment generation and poverty reduction. Cost of investment as well as the development of entrepreneurial capabilities including the revolving nature of our indigenous technology makes it to serve as the propelling force that moves the country's engineering economic growth and development which in most cases, is been facilitated by the adoption of modern technology. Manufacturing is that aspect of the industry that produces tangible goods, services and waste products. It consists of about 80% of industry (Unyimadu and Chiekezie, 2012). For any organization to meet up with the 21st century of competitiveness in business, such organization must be creative. Considering the challenges and the need to adapt and survive in this present knowledge era, research and development department of any manufacturing industry need to be innovative and creative to implement actions that will increase the ability to develop, attract and retain talents. Creativity is viewed as the process of generating business ideas and needs in an enabling environment conducive to both the development of ideas and their implementation to facilitate organizational growth (European Innovation Score Board, 2009). However, business enterprises need to constantly be creative in order to ensure growth and success in the competitive global environment.

In order to grow, manufacturing industries have to adapt with the spirit of creativity and innovation approach that will enable them gain a competitive edge in the dynamic business environment (Mwangi and Namusonge, 2014). Due to the market competitiveness, organizations are expected to be creative in developing new products and services that will survive in the highly competitive environment (Epetimehin, 2008). Modern Technology helps firms to improve in their business processes and decrease cost. Modern Technology is considered as one of the strategic resources that has contributed to firms' performance and forms the cornerstone of gaining competitive advantage (Kraaijenbring et al., 2010). Modern technological adaptation is a major determinant of innovation capacity. Boosting indigenous technological capability thus remains a major development challenge in Nigeria. The challenge is more pronounced in the industrial sector because industry forms the center of technological activities in any economy. In a national system of innovation, firms which constitute the industry are the centers of technological innovation that sustain economic growth (Freeman, 1995; Muchie and Baskaran, 2009).

Nigerian production systems are still at a very low-level stage since many of its operators are still using the traditional-based approaches rather than adopting modern technologies (Apulu, 2012). Most Nigerian manufacturers are of the view that constant power failure which causes increase in cost of production affects selling price. Nigerian products suffer mostly due to the common Nigerian mentality that any of her locally made products are sub-standard, so must be lower in market price. An average Nigerian operator would always hinge his failure on lack of access to finance, some others think otherwise, arguing that inappropriate management skills, lack of adoption of change and modern technologies, difficulty in accessing global market, lack of entrepreneurship skills and technical know-how, poor infrastructure etc. are largely responsible (Johnson, 2011; Akingunola, 2011; Sanusi, 2011). However, the obsolete technologies and practices implemented cannot meet the production and services challenges of today (Vision 2020 Technical Report on SMEs, 2009). Based on these backdrops, this paper is of the view that modern manufacturing technology and practice will serve as a veritable tool to concern individuals as well as government reawakening for national economic growth.

1.1 The Manufacturing Industry

Libanio (2006) through the use of Kaldor's first law defined manufacturing sector as the engine of growth of the economy. Manufacturing sector refers to those industries which are involved in the manufacturing and processing of items and indulge in either creation of new commodities or in value addition (Adebayo, 2010). To Dickson (2010), manufacturing sector accounts for a significant share of the industrial sector in developed countries. The final products can either serve as finished goods for sale to customers or as intermediate goods used in the production process. According to Loto (2012), manufacturing sector is an avenue for increasing productivity in relation to import replacement and export expansion, creating foreign exchange earning capacity, raising employment and per capita income which causes unrepeatable consumption pattern. Mbelede (2012) opined that manufacturing sector is involved in the process of adding value to raw materials by turning them into product.

Thus, manufacturing industry is the key variable in an economy and motivates conversion of raw material into finished goods. Manufacturing industries creates employment which helps to boost agriculture and diversify the economy on the process of helping the nation to increase its foreign exchange earnings (Charles, 2012).

Manufacturing industries came into being with the occurrence of technological and socio-economic transformations in the Western countries in the 18th-19th centuries. This period was widely known as industrial revolution. It all began in Britain where labor intensive textile production was replaced with mechanization and use of fuels. Manufacturing sector is categorized into engineering sector, construction sector, electronics sector, chemical sector, energy sector, textile sector, food and beverage sector, metalworking sector, plastic sector, transport and telecommunication sector (Economic Watch, 2010).

1.2 Historical Performance of the Nigeria Manufacturing Sector

Adenikinju and Chete (2002) conducted an empirical analysis of the performance of the Nigerian manufacturing sector over a 30-year period and observed that the sector was performing with satisfactory growth levels from 1970 to 1980. However, after that phase there was a sharp decline in the growth and profitability of the Nigerian manufacturing sector. Especially, after 1983, the negative effects of the oil price collapse in the international oil market can be clearly seen on the sector's performance. Due to that global oil crisis, the revenues of the Nigerian government sharply declined which resulted in reduction in foreign exchange earnings. This in turn forced the government to take several initiatives with the intention of strictly controlling its trade. There were several import duties enacted in the form of import licenses and tariffs, and some quantitative restrictions were also imposed on the importation of certain items. As a result, the manufacturing sector was badly affected because the manufacturers faced multiple problems when obtaining raw materials and spare parts for their products and processes.

As a result of massive cutbacks in raw materials, spare parts and new technologies, many of the country's industries were shut down and the capacity utilization in the manufacturing sector declined. For example, between 1977 and 2007, the Nigerian bicycle manufacturing subsector recorded a systematic decline in capacity utilization by about a total of 485%; that is, from 948,000 units of bicycles in 1977 to 161, 500 units of bicycles in 2007. Adenikinju and Chete (2002) also observed this disturbing trend in most of the other manufacturing sub-sectors in the country.

Dipak and Ata (2003) stated that the effects of the trade restrictions resulting from the oil price crisis were clearly observed in the form of a 25% decline in the real output of the manufacturing sector from 1982 to 1986. Although the annual growth rate of the Nigerian manufacturing sector was 15% between 1977 and 1981, the government trade restriction measures resulted in the succeeding sharp decline in the growth rate of the sector.

1.3 Manufacturing Industry and Nigeria Economic Development

According to Dibua and Dibua (2012), industrial development is arguably the engine of sustained long-term economic development. Industrial development represents a deliberate and sustained application and combination of suitable technology, human resources, management techniques and their resources to improve the production system. The economic argument for embarking on industrial development is that rising productivity in the economy depends largely on industrial performance often obtained through technological innovation, which results from improved factor input combinations. This higher wage rate associated with the modern industrial sector attracts the surplus labor from the subsistence traditional sectors have advanced. Industrial development has produced synergy between the two sectors, and net economic welfare has improved considerably for every strata of the population.

The share of the manufacturing sector in the total GDP of the country also clearly declined during this era. In 1977 there was a 4% increase recorded in the manufacturing sector share in GDP and this reached the level of 13% in 1981, but after that it declined to less than 10% in just a few years. Dipak and Ata (2003) and Adenikinju and Chete (2002) concluded that the unavailability and inadequacy of the companies' access to the raw material, spare parts and modern equipment were among the major factors that contributed towards the decline in the growth rate of the manufacturing sector especially after 1981. Hence, the oil price shock is identified as the reason behind the policies that ultimately resulted in the decline of manufacturing sector's growth.

From 1982 to 1986, Nigeria's value added in manufacturing fell considerably partly because of inefficient resources allocation caused by distorted prices and prohibition of importation. Between 1986 and 1988 the World Bank induced structural adjustment program (SAP) and it increased the contribution of the manufacturing industry to GDP which grew 8 percent in 1988. The deregulation of foreign exchange market was also reckoned to make manufacturing industries more competitive by increasing input costs (CBN, 2010). Looking at the manufacturing sector share in the GDP in recent years (1990-2019), it has not been relatively stable. In 1990, it was about 5.5% while it drops to 2.22% in 2010. Also, at the same period, the overall manufacturing capacity utilization grew from 40.3% in 1990 to 58.92% in 2019. GDP from manufacturing in Nigeria averaged ₦1413401.85 on from 2010 until 2019, reaching an all-time high of ₦1718985.30 on in the third quarter of 2014 and a record low of N1875408.17 Million in the first quarter of 2010. GDP from Manufacturing in Nigeria decreased to ₦1608461.83 in the first quarter of 2019 from ₦1686416.37 in the fourth quarter of 2018 (CBN, 2019).

1.4 Challenges of the Manufacturing Industries in Nigeria

In recent time, some manufacturing industries in Nigeria have been characterized by declining productivity rate, by extension decrease in employment generation, which is caused largely by inadequate modern technologies due to electricity supply, smuggling of foreign products into the country, trade liberation, globalization, high exchange rate, and low government expenditure. Therefore, the slow performance of manufacturing sector in Nigeria is mainly due to massive importation of finished goods and inadequate financial support, which has resulted in the reduction in innovation, utilization of capacity of modern technologies and input of the manufacturing sector in the economy (Tomola et al., 2012). Furthermore, in Nigeria, the level of growth in the manufacturing sector has been affected negatively because of high interest rate on lending and this high lending rate is responsible for high cost of production in country's manufacturing sector (Adebiyi, 2001; Adebiyi and Babatope, 2004; Rasheed, 2010). Hence, Okafor (2012) observed that the level of Nigerian manufacturing industries' performance will continue to decline because of low implementation of government budget and difficulties in assessing raw materials and stiff competition with foreign firms.

2.0 MODERN TECHNOLOGIES IN THE MANUFACTURING INDUSTRY

The manufacturing industry has always had an appetite for technology. From big data analytics to advanced robotics, the game-changing benefits of modern technologies are helping manufacturers reduce human intervention, increase plant productivity and gain a competitive edge (Noria Corporation, 2019). Sophisticated modern technologies, such as artificial intelligence, the internet of things and 3-D printing among others, are shaping the future of manufacturing by lowering the cost of production, improving the speed of operations and minimizing errors. Since productivity is critical to the success of a manufacturing plant, every manufacturer is expected to make significant investments in these technologies. Five technologies that are positively impacting the manufacturing industry include;

i. The Industrial Internet of Things

The industrial internet of things (IoT) is an amalgamation of various technologies, such as machine learning, big data, sensor data, cloud integration and machine automation. These technologies are being employed in areas like predictive and proactive maintenance, real-time monitoring, resource optimization, supply-chain visibility, cross-facility operations analysis, and safety, enabling plant managers to minimize downtime and enhance process efficiency. For instance, regular maintenance and repair are essential for smooth plant operations. However, not all equipment and devices need maintenance at the same time. The IIoT allows plant managers to employ condition monitoring and predictive maintenance of the equipment. The real-time performance monitoring helps them plan their maintenance schedule around when it is actually necessary, reducing the likelihood of unplanned outages and the ensuing loss of productivity. Similarly, IoT-enabled and sensor-embedded equipment can communicate data that helps the supply-chain team track assets (using RFID and GPS sensors), take stock of inventory, forecast, gauge vendor relations and schedule predictive maintenance programs (Noria Corporation 2019).

ii. Big Data Analytics

Big data analytics can offer several ways for improving asset performance, streamlining manufacturing processes and facilitating product customization. According to a recent survey by According to Louis (2016), 68 percent of American manufacturers are already investing in big data analytics. These manufacturers are able to make informed decisions using productivity and waste performance data provided by big data analytics, lowering operating costs and increasing the overall yield (Noria Corporation, 2019).

iii. Artificial Intelligence (AI) and Machine Learning

For several decades, robotics and mechanization have been employed by manufacturers to increase productivity and minimize production costs per unit. AI is helping production teams analyze data and use the insights to replace inventory, reduce operational costs and offer seamless quality control over the entire manufacturing process. The era of unintelligent robots engaged in cyclical production tasks has ended. AI and machine learning are making it possible for robots and humans to collaborate with each other, creating agile manufacturing processes that learn, improve and make smart manufacturing decisions. Consequently, manufacturers can employ industrial robotics and smart automation to manage mundane tasks and focus their time and resources on revenue-generating tasks such as research and development, product line extension and better customer service (Noria Corporation, 2019).

iv. Printing or Additive Layer Manufacturing Technology

This set to make a huge impact on high-end industries such as aerospace, mining machinery, automobiles, firearms, commercial and service machinery, and other industrial equipment. This revolutionary technology allows manufacturers to create physical products from complex digital designs stored in 3-D computer-aided design (CAD) files. Materials such as rubber, nylon, plastic, glass and metal can be used to print real objects. In fact, 3-D bio printing has made it possible to manufacture living tissue and functional organs for medical research. Unlike the traditional manufacturing process, 3-D printers can create complex shapes and designs at no additional cost, offering greater freedom for designers and engineers. Moreover, the increasing applications of 3-D printing in manufacturing are giving rise to manufacturing as a service (MaaS), enabling companies to maintain an up-to-date infrastructure that caters to multiple clients and negating the need to purchase new equipment (Noria Corporation, 2019).

v. Virtual Reality

Virtual reality (VR) is simplifying the product design process by eliminating the need to build complex prototypes. Designers and engineers are using VR to create realistic product models, allowing them to digitally see their designs and troubleshoot potential issues before starting production. Clients can also review and interact with these digital designs, simulations and integrated devices, significantly reducing the time needed for designing to manufacturing the finished product. For instance, automobile manufacturers are now using virtual reality to ensure their cars are tested at an early phase of the vehicle development process, decreasing the time and cost involved in modifying the designs, tolerances and safety features (Noria Corporation, 2019).

2.1 The Nigeria Manufacturing Industry and Modern Technologies

Adeoti (2002) investigated investment in technology by manufacturing firms in southwest Nigeria and how technology investment related factors affect the performance of manufacturing firms using data obtained from a survey of Nigerian firms in 2011 and found that investments in technology are dominated by imported technologies and technology investments are not directly targeted at export potentials and global competitiveness of firms.

Akpan (2011) in his study viewed nation's economic development through adequate industrialization. The study is empirically inclined, examining the relationship between industrialization and economic development with focus on Nigeria. The Ordinary Least Square (OLS) technique was adopted in line with diagnostic test for the model. Finally, the study advocates that a responsible government should embrace technological industrialization for meaningful economic growth so as to enhance export and discourage import.

According to Ezeilo (2014), the following concepts are needed to help improve the manufacturing firms in Nigeria. They include:

i. Investment in ICT (E-business Facilities)

Investment in ICT is an important factor that has enabled the competitiveness of many successful economies in recent decades (Amini-Philiphs and Elijah, 2019). However, while Nigerian manufacturing firms still lag behind in the use of ICT in the production process; Nigerian firms are beginning to employ ICT for operations management and other e-business activities. Adeoti (2002), defined e-business to encompass the application of ICTs in all business processes such as office automating, production processes, coordination with other plants, customer relation management, supply chain management, and management of distribution network.

ii. Investment in Skills Upgrading

For the purpose of this study, we conceive investment in skills upgrading to entail investment in training activities that enable better and efficient operation of machines and equipment. However, skills upgrading is generally reckoned as the outcome of learning mechanisms that enable firms improve their technological capability endowment. Skills upgrading fosters cross fertilization of knowledge, and thus enhances technological innovation and health friendly manufacturing processes.

iii. Investment in Technology Hardware

This variable represents firm's implementation of a programme of reengineering that brings in new production equipment/machines or reengineering that improve existing production equipment/machines. Many Nigeria firms are known to use second hand machines/equipment due to capital constraints, and some even use production equipment that are obsolete. It is assumed that an immediate challenge that faces firms would be the necessity to embark on a reengineering programme that would replace obsolete or inefficient machines/equipment in order to significantly improve production performance.

iv. Technological Collaboration with Foreign Firm(S)

Adeoti (2002) observed that technological collaboration between local and foreign firms can have positive impact on performance of firms. This can be in the form of foreign direct investment in a subsidiary of a multinational firm or technology licensing, technical agreements, trademarks, and so on.

3.0 THE IMPACT OF MODERN TECHNOLOGIES ON MANUFACTURING INDUSTRIES

Production fundamentally impacts economic structure at global, regional, national and local levels, affecting the level and nature of employment, and today is inextricable from environmental and sustainability concerns, considerations and initiatives. Collectively, the sectors of production have been the source of economic growth in developed and developing nations alike, a major source of employment for a rapidly evolving and increasingly skilled workforce, and they continue to be the dominant focus of innovation and development efforts in most countries.

The transformative potential of technology in production systems is widely recognized, even while the precise configuration and extent of the possible transformation remain unknown. Trends towards higher levels of automation promise greater speed and precision of production as well as reduced exposure to dangerous tasks for employees. New production technologies could help overcome the stagnant productivity of recent decades and make way for more value-added activity. The extent of automation is, however, causing significant anxiety about issues of employment and inequality. The application of new technology to manufacturing industry is, in the view of the ‘modern technology’ literature, changing its nature in several respects. In contrast with the old ‘mass production technological paradigm’, the introduction of modern technology leads to qualitatively different command and control structures, work organization patterns and competitive strategies. Fifteen (15) Bureaucratic and centralized lines of command and communications are replaced by flatter hierarchies and informal control mechanisms based on goal setting and participatory decision-making. Separate functional departments, standard routines and procedures, and individual job definitions are also displaced by interactive and cooperative links and adaptable procedures between departments, groups and individuals. Labour is no longer seen as a cost or as doing a single specialized function, but as human capital, and therefore there is much more emphasis on having a multi-skilled, creative, knowledgeable, trustworthy and responsible work force. Finally, arm’s length relationships with suppliers and competitors are displaced by collaborative links with suppliers, customers and sometimes with competitors. Competition is no longer based on cost cutting but on continuous innovation and fast market response.

One of the most important aspects of the modern technology is the ’flexibility’ they have introduced into the production process. Production facilities can now produce a far wider range or scope of products than before. Flexibility has an ’operational’ element which is related to the capacity to adjust easily output proportions for a given range of individual goods. It also has a 'strategic' element which refers to the capacity to alter the product mix by introducing new products or modifying the quality of existing ones.

4.0 CONCLUSION

Nigerian production systems are still at a very low level since many of its operators are still using the traditional-based approaches rather than adopting modern technologies. The manufacturing industry has always had an appetite for technology. From big data analytics to advanced robotics, the game-changing benefits of modern technologies are helping manufacturers reduce human intervention, increase plant productivity and gain a competitive edge. Sophisticated modern technologies, such as artificial intelligence, the internet of things and printing among others, are shaping the future of manufacturing by lowering the cost of production, improving the speed of operations and minimizing errors. Since productivity is critical to the success of a manufacturing plant, every manufacturer is expected to make significant investments in these technologies. This work, therefore suggests that the Nigerian engineers take some time to think about the problem of achieving better product design/manufacturing process integration, particularly as it relates to assembly automation and design for manufacturability. The work showed that when modern manufacturing technology and practice are employed (with automation in mind), there would be significant reduction in manufacturing costs of products, and improvement in the effectiveness of equipment thereby leading to national economic growth.

Suggestions

With regards the foregoing, the following are recommended by the researcher:

1. The Nigeria government should invest more in ICT (E-business facilities)
2. The Nigeria government and manufacturing industry should invest in skills upgrading of its workers.
3. The Nigeria government and manufacturing industry should invest also in technology hardware.
4. There should be collaboration between foreign firm(s) and the Nigeria government and manufacturing industries.

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AUTOMOTIVE ASSEMBLY PROCESS PERFORMANCE ANALYSIS FOR IMPROVED PRODUCTIVITY

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ABSTRACT:

The Nigerian automobile manufacturing industry in general and the automotive assembly process in particular has over the years been faced with so many challenges. This paper therefore presents analyzed performance of an automotive assembly plant for improved productivity and sustainability. The production profiles for six months were collected. The number of workers, absenteeism, number of equipment, number of material handling equipment, and wasted time in the various work stations were also collected. The overall equipment effectiveness, total effective equipment performance, hour per unit, organization hour per unit were the various tools used in analyzing the data. After the analysis, the organization hour per unit was showed to be 148 hours, which implies that it takes the organization 148 hours to assemble a car. The overall equipment effectiveness was also shown to be 76.19%, which is not up to the world class standard of 85%. The losses in overall equipment effectiveness (OEE) were shown to be as a result of machine breakdown, shortages of operators, power failure, and material shortages. The average production volume was found to be 256 units per month. Total effective equipment performance was found to be 61.89% meaning that the assembly plant is still underutilized. More vehicles can still be assembled.

KEYWORDS: Automotive assembly, Process performance, Performance analysis, Overall equipment effectiveness, Productivity.

1.0 INTRODUCTION

Automotive assembly process is amongst the utmost frequently used production system. An automotive assembly process is a succession of workstations at which jobs connected to assembly of an automobile product are accomplished (Becker & Scholl, 2006). It is an assembly method which has work stations linked together by material handling equipment so every product passes from one operation straight to the ensuing operation (Özcan & Toklu, 2009). According to Maqsood *et al.* (2011), an automotive assembly process comprises of lots of workstations which perform some procedures happening on a work piece in a cycle period. Consequently, every particular product follows a pattern sequentially; also the total outputs predicted at the finish of line are identical (Kara *et al.*, 2009). The difficulty in the way of assembling a product rest on its parts numbers and its assembly levels. Products identical at the conclusion of the assembly line are categorized as single model assembly line. Furthermore, most assembly lines were developed for calculation of cost effectiveness and high superiority assembly of a sole standard product (Boysen*et al.*, 2009).

According to Özcan & Toklu (2009), single-model assembly lines are basically designed to manufacture products of homogeneous standard in mass volume that is not quite appropriate for products of high variety. Because it enables the assembly of work pieces by workers with little training, this type of assembly line is used in a high volume manufacturing area (Cevikcan*et al.*, 2009; Elijah, 2019). The intent of this paper is to ascertain the vital challenges in Nigeria automotive assembly plants as well as present alternative techniques to increase the throughput of an automotive assembly process or plant using performance analysis. The performance of automotive assembly process in Nigeria was analyzed for sustainability.

2.0 MATERIALS AND METHODS

The data used in this study was obtained from a Nigerian automobile manufacturing plant. The assembly plant comprises body shop, paint shop and trim chassis final. The techniques used in the data gathering involved verbal discussions with production managers, supervisors, and operators. Also, measurement of procedures with timing equipment's and physical surveillance of the processes were applied to realize the goal and intentions of the study. To analyze automotive assembly line performance, performance parameters of various work stations that includes machine productivity and manpower productivity were measured. Assembly processes in numerous phases in automotive line were gotten by applying stop watches in time studies method. Stop wristwatches were used in determining time of numerous processes taking place in automotive assembly plant.

The production profile for 6 months that is from July to December 2018 is shown in Table 1, the manufacturing target for every month and week was also provided in the table. The table also displays the number of products assembled for every single week of each month, and it also displays the rework.

To calculate the percentage of assembled products produced every month that is on time delivery and the work in process, a performance analysis was done. Below are the performance parameters (Table 2).

Table 1: Production Profile for Six Months

Mon	Production target per month	Week 1	Week 2	Week 3	Week 4	Total Product	Rework/ Reject
		Plan Actual Qty	Plan Actual Qty	Plan Actual Qty	Plan Actual Qty		
Jul	300	75 68	75 70	75 56	75 66	260	24
Aug	300	75 64	75 58	75 66	75 67	255	23
Sep	300	75 70	75 67	75 65	75 54	256	21
Oct	300	75 55	75 66	75 65	75 63	249	24
Nov	300	75 60	75 64	75 59	75 67	250	26
Dec	300	75 69	75 68	75 58	75 69	264	26

Table 2: Performance Parameters

Month	On Time Delivery in%	Work in Process(units)
July, 2018	83.2	40
August, 2018	79.8	45
September, 2018	80.3	37
October, 2018	81.7	45
November, 2018	78.5	46
December,2018	80.0	39

Average	80.6%	

$$P(W)=\sum wi) \qquad \text{Equation (1)}$$

Where P(w) = production volume for six months

$$\sum wi = w1 + w2 + w3 + \cdots + wn \qquad (2)$$

X= Average Production Volume

$$X= w1 + w2 + w3 + \cdots + wn \qquad (3)$$

Where wn= week 1 to week n

n= number of weeks

2.1 Absenteeism

Absenteeism is a routine pattern of non-appearance from a responsibility or duty lacking good reason. In general, absenteeism is unintended nonappearance. Table 3 shows number of workers in case study automobile assembly plant absent in every work station from July to December 2018.

Table 3: Number of workers absent in Each Station for six months

Months	Body Shop	Paint Shop	Trim Chassis-Final	Total
July, 2018	2	1	2	5
August, 2018	1	-	2	3
September,2018	-	1	-	1
October, 2018	1	1	1	3
November, 2018	2	1	1	4
December, 2018	1	-	1	2

2.2 Wasted Times

In automotive plants, events which do not add value to automotive assembly process is referred to as wasted times. It has to do with the activities and the time consumed by each activity in the assembly line. The time wasted in automobile assembly line for every event and the rate at which it occurs is shown in Table 4.

Table 4: Wasted times

S/N	Activities	Downtime (mins)	Frequency
1	Motion of trolley	5	Once every three hrs.
2	Returning of vacant trolley	9	Once every two hrs.
3	Categorization of parts	7	Once every three hrs.
4	Disposal of undesirable materials	6	Once in every 4 hrs.
5	Looking for suitable tools	3	Once every one and half hrs.
6	Dispatching of completed unit	10	Once every two hrs.
7	Gathering of dropped bolts, screw, and nuts	5	Once every one hr.
8	Rework	15	Once every five hrs.

2.3 Downtimes

Downtime is the time during which a machine is out of action or not ready for use. Downtime includes any unforeseen occurrence that brings the production process to halt. A material concern, scarcity of operators or impromptu maintenance may well prompt production to halt. Main downtime exists as time when every person in a station is not operational as a result collapses of machineries and power let-down on automotive assembly line. The downtimes are shown in Table 5.

Table 5: Main downtime meant for the three main departments

Month	Station	Causes	Time (hrs.)
July	All	Power failure	3
August	Body shop	Overhead crane failure	2
September	Body shop/ Paint Shop	Overhead crane failure	2
October	Trim chassis Final	Overhead conveyor system failure	1
November	All	Power failure	2
December	Body Shop/ Trim chassis	Forklift failure	3

2.4 Productivity in units/ employee

Productivity is defined as a Key performance indicator that measures total number of units, having no difference between several products, manufactured via number of workers, intended for the plant total as well as for every well thought-out organizational unit, splits. Labour Productivity is defined as ratio of production volume and number of workforces.

Let P = Production volume

$$\text{Productivity} = \frac{Production\,Volume}{Manpower} \times \frac{229}{Working\,Days}\left(\frac{units}{employee}\right) \quad (4)$$

where, 229 is a standard which stands as number of working hours yearly.

2.5 Overall Equipment Effectiveness

In this paper, the efficiency of equipment was measured through OEE. This is used in monitoring the productivity of automated and semi-automated manufacturing system. Three factors are responsible for determining overall equipment effectiveness. The three factors responsible are availability of machines, performance, as well as quality of product. OEE is a global standard for calculating efficiency of manufacturing. It recognizes percentage of production time that is actually productive.

$$\text{OEE} = \text{A} \times P \times Q \quad (5)$$

2.6 Performance

Performance of machinery is percentage of actual run-rate to ideal run-rate. Performance looks at everything that makes manufacturing process to function at a lesser speed when you compare it to the all-out potential speed when the machinery is operating.

3.0 RESULTS AND DISCUSSION

3.1 Time Study

The time expected time to perform tasks every day is 9 hours. On the other hand, majority of this time were expended on events which never added any value to assembly plant, decreasing throughput of organization in addition with work in progress inventory. The labour number for every work station, the working time expected every day, the working time total each labour, each day, each week and month is provided in Table 6.

Table 6: Every hour, every day, every week, and Labour time every month

Workshop	Unit Labour	Time (hour/labour)	Total time (hour/day)	Total time (hour/week)	Total time (hour/month)

Body shop	52	9	468	2340	9360
Paint shop	18	9	162	810	3240
Trim Chassis final	87	9	783	3915	15660

3.2 Work-in-Progress, Target and Production Volume.

The average production volume of the company is 256 units for every month as shown in Table 7, on the other hand the manufacturing target is 300 units every month which means that the time delivery average of bus is simply 80.6 % (see Table 2). From the observations, the company was unable to reach its target in the six months (see Figure 1).

Table 7: Displaying Month, Target, Volume of Production and Work in Progress

Month	Target(units)	Production volume	WIP((units)
July	300	260	40
August	300	255	45
September	300	256	37
October	300	249	45
November	300	250	46
December	300	264	39

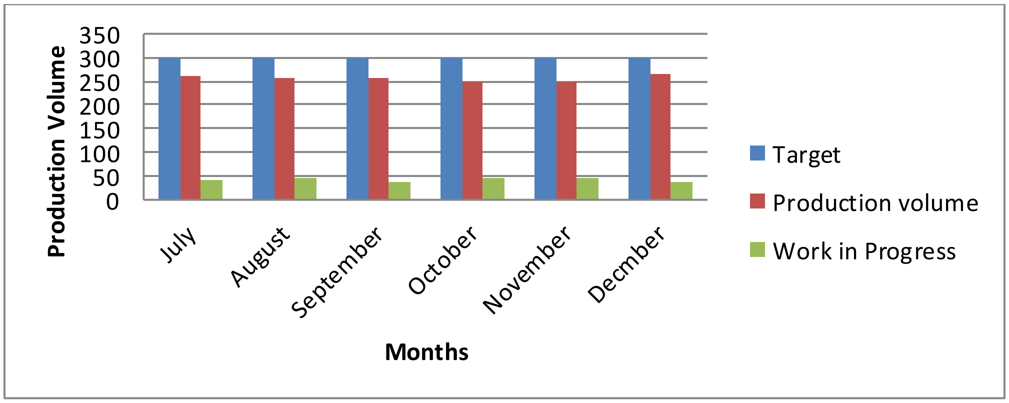

Figure 1: Comparison of Target, Production volume and WIP

3.3 Productivity

The key performance indicator applied in measuring product units assembled in a month is known as Productivity. It displays the production volume in assembly plant. Management can use the value in Table 8 in the course of the preparation phase of project, in knowing expected assembly for a certain month. This specifies working days, number of labours, as well as the production volume. This enables the organization to be very effective in making decisions, design and preparation of the job.

Table 8: Productivity

Month	Production vol.(units)	Labour (units)	Work day	Productivity
July	260	249	21	11.39
August	255	246	22	10.79
September	256	244	20	12.01
October	249	247	23	10.04
November	250	245	22	10.62
December	264	251	21	11.47

3.4 Overall Equipment Effectiveness

Overall Equipment Effectiveness is fundamentally a tool applied for benchmarking with first-class overall equipment effectiveness as well as enhancing the productivity of machine. This OEE expresses exactly how effective our production equipment's performs in relation to its fully loaded capacity in the course of the calculated production time.

From Table 9, the OEE is 76.19%. We know from Table 10 that world class OEE is 85%. So the OEE determined is not up to the standard OEE (see figure 2). These losses present in overall effective equipment are quality losses, speed losses, and downtime losses. Overall equipment effectiveness of the operation is affected by these losses.

Table 9: Overall Equipment Effectiveness

OEE Factors	OEE	OEE in %
Availability	0.875	87.5%
Performance	0.9252	92.52%
Quality	0.9412	94.12%
Overall OEE	0.7619	76.19%

Table 10: World Class OEE

	World Class OEE	
OEE Factors	World Class OEE	My OEE
Availability	90%	87.5%
Performance	95%	92.52%
Quality	99.9&	94.12%
Overall OEE	85%	76.19%

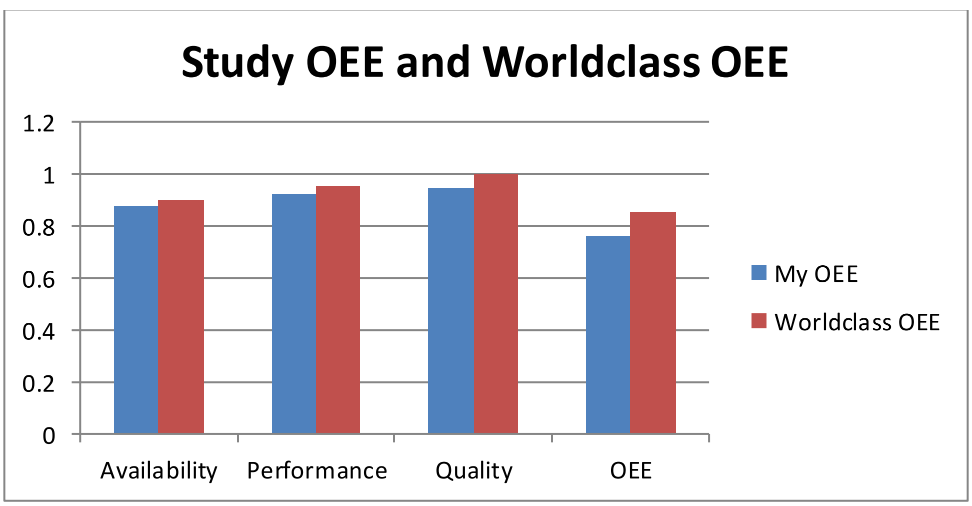

Figure 2: Present OEE and World class OEE

3.5 Imbalance of the Assembly Line

Imbalance of assembly line was as a result of not having sufficient workers in the assembly line caused by absenteeism. From Figure 3, a total of 18 workers were absent in the course of the assembly process along the line. The work was interrupted due to having limited number of workers operating in the assembly plant.

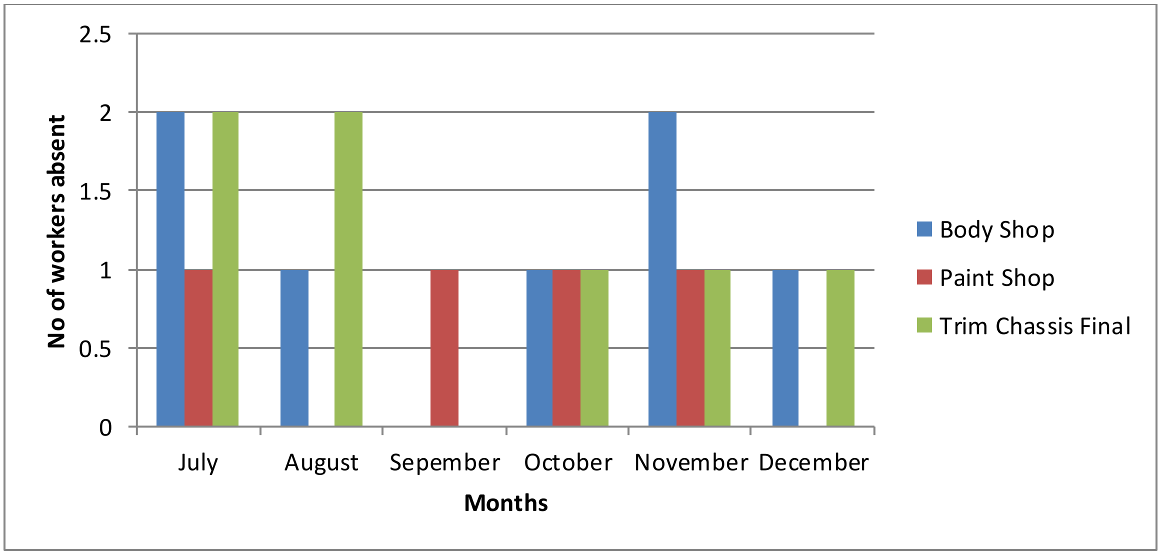

Figure 3: Absenteeism

3.6 Total effective equipment performance

This is used for analysis of capacity utilization. Total effective equipment performance is being determined weekly. TEEP is basically a performance metric responsible for providing insights towards the exact capacity of assembly processes. The total effective equipment performance calculated from Table 14 is 61.89%. This result shows that the plant is still under-utilized. It means that so much more can still be assembled in the plant.

Table 14: Total Effective Equipment Performance

Parameters	**Machine P**	**Machine Q**	**Machine R**	**Assembly PQR**
Demand in pieces	3600	2090	1600	7290
Total production time in hrs.	45	45	45	45
Shutdown losses	5	8	10	11

hrs.				
Capability in pieces	4300	2650	1950	8900
TEEP	**0.7442**	**0.6485**	**0.6382**	**0.6189**
TEEP in %	**74.42%**	**64.85%**	**63.82%**	**61.89%**

4.0 CONCLUSION

This study was done to analyze the performance of a Nigerian automotive assembly plant for improved productivity. Meeting the demand of customers is a key challenge in the present automotive sector. The following performance indices were gotten from our study: the average production volume of automobile assembly line is 256 units for every month and its average on time delivery is 80.6 %. Nine hours was the time period the workers spent every day. Value added events and non-value-added events were discovered. They were analyzed and it was learnt that 60 minutes were wasted on non-value-added events. During the analysis, it was discovered that 13 hours were wasted on unplanned downtime which was a result of collapse of machineries and power let-down. Absenteeism was a result of lack of workers in assembly plant. The labor productivity is 66.32 %. The overall equipment effectiveness is 76.19% as compared to the standard OEE which is 85%. The total effective equipment performance is 61.89%. This result shows that the plant is still under-utilized. It means so much more can still be assembled in the plant. Sequel to the study outcome, preventive maintenance should be inculcated into the plant.

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AN ANALYTICAL STUDY OF A UNIAXIAL BUCKLING OF RECTANGULAR PLATE WITH ARBITRARY CLAMPED/SIMPLY-SUPPORTED BOUNDARY CONDITION UNDER UNIFORMLY COMPRESSIVE LOADING

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Abstract:
In this paper, an analytical study of a uniaxial buckling of rectangular plate with arbitrary clamped/simply-supported boundary condition subjected to a uniformly compressive loading is presented. The energy equation which was transformed to compatibility equations of three-dimensional plate and presented for the determination of the relations between the rotations and deflection. The solution of compatibility equations yields the exact plates shape function which is derived in terms of trigonometric and polynomial displacement and rotations. Similarly, by minimizing the energy equation with respect to the out of plane displacement, the direct governing equation was formulated. The solution of governing equation yields the deflection coefficient of the plate. By minimizing the energy equation with respect to deflection coefficient after the action deflection and rotations equation were substituted into it, a more realistic formula for calculation the critical buckling load is established. The proposed method unlike the refined plate theory (RPT), considered all the six stress elements in the analysis. The critical buckling loads from the present study using polynomial are slightly higher than those obtained using trigonometric theories signifying the more exactness of the latter. It is evidenced from the discussion above that the results of this present study using the established exact 3-D model for the thick plate analysis is satisfactory and better when compared to conventional approach (RPT). The overall average percentage differences between the two functions recorded are 3.8%. This shows that at about 96% both approach are the same and can be applied in confidence for analysis of plate of any thickness.

Keywords: uniaxial buckling, CCSS rectangular plate, compressive load, energy method, 3-D plate analysis.

1.0 INTRODUCTION

The captivating properties; light weight, economy, and ability to withstand loads, etc. of plate materials have made them to be widely used in different engineering field (Onyeka et al, 2021). Plate structures are used in structural engineering, mechanical engineering, and aerospace engineering etc., in making retaining walls, floor slabs, bridges, railways, ships (Ghugal and Gajbhiye, 2016, Onyeka, and Osegbowa, 2020). Plate has been grouped based on thickness as: thick, moderately thick and thin plates (Chandrashekhara, 2000) and also based on their material properties and deformation nature as: orthotropic, isotropic, anisotropic plates, etc., based on shape as: triangular, rectangular, circular plates etc. (Nwoji et al, 2017 and Onyeka et al, 2020).

It is generally known that transverse compressive loads are the main loads which plates are usually subjected and they mainly act on the plates' mid plane. The in - plane compressive loads are forces which can be uniformly distributed over the plate's depth and applied at the edge parallel to the plate's middle plane (Timoshenko and Gere, 1963). The author in (Michael, et al, 2020) stated that in - plane compressive loads can either be applied uniformly or non - uniformly on the plate boundaries, uniaxial or biaxial. The equilibrium of plates can be affected when subjected to the in - plane compressive forces. The plate can be in stable equilibrium if the in-plane compressive forces are small but if a little additional force leads to a large response - which causes the plate to be unstable, then result to buckling (Sayyada, and Ghugal, 2012). Buckling can either be elastic or inelastic - where elastic buckling occurs when the elastic limit of the material is greater than the critical buckling load. Plate fails when huge deflection and bending stresses occur due to the application of in - plane compressive load beyond the critical values - as such, it is vital to study and analyze the stability of plates in order to obviate failure (Wang, et al, 2005, Sachin et al, 2015).

The analysis of plates has been of paramount importance to many researchers (Ibearugbulem et al, (2020), Kirchhoff, (1850), Sayyad and Ghugal (2012) and different theories and methods have been deployed for this purpose by different researchers. The generally well-known classical plate theory (CPT) developed by the author in (Kirchhoff, 1850), can be applied in the buckling analysis of thin plates only due to the non-inclusion of shear deformation which is dominant in thick plate. The CPT over-estimates the critical buckling loads when used in the analysis of thick plate (Sayyad and Ghugal, 2012). The gap in CPT in the analysis of thick plates was bridged by the formulation of refined plate theories (RPT) (Ibearugbulem et al, (2014), and Ibearugbulem et al, (2016). The RPT is a shear deformation theory which is based on the assumption that the vertical line which is normal to the mid-surface before deformation do not remain normal after deformation, but remain straight (Reissner, 1945). The RPT: first order shear deformation theory (FSDT) has shear correction factor as its limitation (Mindlin, 1951 and Yang, & Qian, 2017). The higher order shear deformation theories (HSDT) which is an improvement on the FSDT, due to its avoidance of shear correction factor has been used by different researchers in the analysis of thick plates (Gunjal et al, 2015, Ezeh et al, 2018, Ibearugbulem et al, 2018, Onyeka et al, 2019).

The results of the buckling analysis of thick plates using shear deformation theories from previous scholars proved that 2-D or incomplete 3-D analysis results for thick plates with very high depth to length ratio is unreliable (Onyeka et al, 2021 and Vareki et al, 2016). This is because a thick plate is a 3-D member, as such, should be analyzed as such for a better result to be achieved by putting all the directions (x, y, and z) into consideration which amount into analysis having the whole six stresses and strain elements in the mathematical relations. Thus, the FSDT and the HSDT are regarded as an incomplete 3-D analysis of thick plates, as such, for complete thick plate analysis, 3-D plate theory that considers the three directions needs to be employed (Vareki et al, 2016, Onyeka et al, 2021). However, no much study has been carried out by researchers, by considering the 3-D member for stability analysis of thick plates with a view to obtaining the critical buckling loads by using the exact displacement function derived from compatibility equations.

In Vareki et al, (2016), the authors did a study on the 3-D elasticity buckling solution for rectangular thick plate that was simply supported with the use of displacement potential method. They obtained analytical solution from the method they applied for linear elastic buckling for the rectangular thick plate with simply supported edges. But they an assumed the displacement function which may not be reliable, and also only considered thick rectangular plate whose edges were simply supported without applying polynomial shear deformation plate theory.

The author in (Onyeka et al, 2021) studied the application of new trigonometry shear deformation plate theory in the buckling solution of 3-D rectangular isotropic thick plate which is clamped at one edge and the other remaining edge simply supported (CSSS) under uniaxial compression using the variational method. They carried out the 3-D analysis for the plate's critical buckling by varying stiffness properties and the aspect ratio. Though the method they applied bridged the limitation of author in (Vareki et al, 2016) by formulating their displacement function from the compatibility equation obtained, it can be seen in their analysis that they did not apply polynomial function which is easier to apply especially in the case of complex support conditions. They only considered CSSS rectangular plate, they did not study for other boundary conditions.

This study is aimed at bridging the gap in the literature adopting an analytical approach to obtain a close form solution for a uniaxial 3-D buckling analysis of an isotropic thick rectangular plate subjected to a uniform compressive loading. This work aimed at establishing a more viable formula for computing the critical buckling load of thick rectangular plate which is clamped at adjacent edge and the other opposite edges simply supported using the energy method.

2.0 MATERIALS AND METHODS

Our formulation of the direct governing equation for thick plate under pure bending is based on Fig 1.

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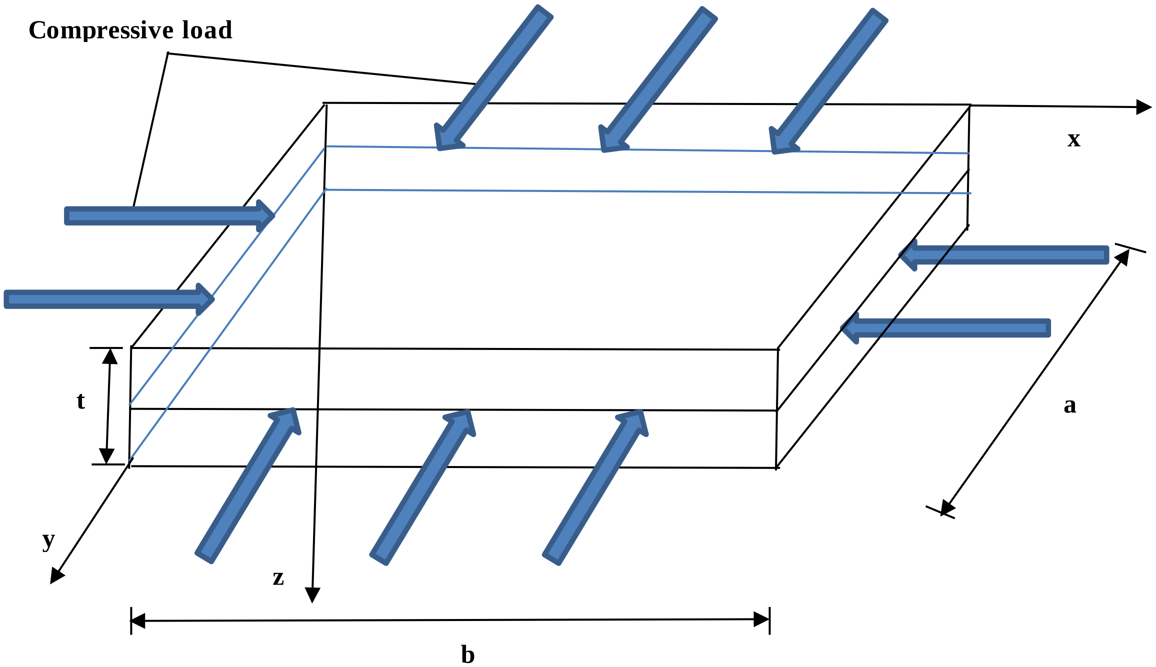

Figure 1: Rectangular thick Plate geometry and co-ordinate system under an axial compressive load

The non-dimensional total potential energy [∏] expression for an elastic three-dimensional plate theory of R and Q coordinates at the span-thickness aspect ratio is in line with author in Onyeka et al, (2021) and presented as:

$$\prod = D\,\frac{(1-\mu)ab}{2a^2(1-2\mu)}\int_0^1\!\!\int_0^1 \left[(1-\mu)\left(\frac{\partial\theta_{sx}}{\partial R}\right)^2 + \frac{1}{\beta}\frac{\partial\theta_{sx}}{\partial R}.\frac{\partial\theta_{sy}}{\partial Q} + \frac{(1-\mu)}{\beta^2}\left(\frac{\partial\theta_{sy}}{\partial Q}\right)^2 + \frac{(1-2\mu)}{2\beta^2}\left(\frac{\partial\theta_{sx}}{\partial Q}\right)^2 \right.$$
$$+\frac{(1-2\mu)}{2}\left(\frac{\partial\theta_{sy}}{\partial R}\right)^2$$
$$+\frac{6(1-2\mu)}{t^2}\left(a^2\theta_{sx}{}^2 + a^2\theta_{sy}{}^2 + \left(\frac{\partial w}{\partial R}\right)^2 + \frac{1}{\beta^2}\left(\frac{\partial w}{\partial Q}\right)^2 + 2a.\theta_{sx}\frac{\partial w}{\partial R} + \frac{2a.\theta_{sy}}{\beta}\frac{\partial w}{\partial Q}\right)$$
$$\left. + \frac{(1-\mu)a^2}{t^4}\left(\frac{\partial w}{\partial S}\right)^2 - \frac{N_x}{D^*}.\left(\frac{\partial w}{\partial R}\right)^2\right]\partial R\,\partial Q \qquad (1)$$

Where:

$$D^* = D\,\frac{(1-\mu)}{(1-2\mu)}$$

2.1 Compatibility Equation

The true compatibility equations in x-z plane y-z plane according the author in (Onyeka et al, 2021) is obtained by minimizing the energy equation with respect to rotation in x-z plane and rotation in y-z plane and equate its integrands to zero to get:

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$$(1-\mu)\frac{\partial^2\theta_{sx}}{\partial R^2}+\frac{1}{2\beta}.\frac{\partial^2\theta_{sy}}{\partial R\partial Q}+\frac{(1-2\mu)}{2\beta^2}\frac{\partial^2\theta_{sx}}{\partial Q^2}+\frac{6(1-2\mu)}{t^2}\left(a^2\theta_{sx}+a.\frac{\partial w}{\partial R}\right)=0 \quad (2)$$

$$\frac{1}{2\beta}.\frac{\partial^2\theta_{sx}}{\partial R\partial Q}+\frac{(1-\mu)}{\beta^2}\frac{\partial^2\theta_{sy}}{\partial Q^2}+\frac{(1-2\mu)}{2}\frac{\partial^2\theta_{sy}}{\partial R^2}+\frac{6(1-2\mu)}{t^2}\left(a^2\theta_{sy}+\frac{a.}{\beta}\frac{\partial w}{\partial Q}\right)=0 \quad (3)$$

Using law of addition, the Equations 2 and 3 will be simplified, then factorizing the outcome gives:

$$\frac{\partial w}{\partial R}\left[(1-\mu)\frac{\partial^2}{\partial R^2}+\frac{1}{\beta^2}.\frac{\partial^2}{\partial Q^2}(1-\mu)+\frac{6(1-2\mu)a^2}{t^2}.\left(1+\frac{1}{c}\right)\right]=0 \quad (4)$$

$$\frac{1}{\beta}.\frac{\partial w}{\partial Q}\left[\frac{\partial^2}{\partial R^2}(1-\mu)+\frac{(1-\mu)}{\beta^2}\frac{\partial^2}{\partial Q^2}+\frac{6(1-2\mu)a^2}{t^2}.\left(1+\frac{1}{c}\right)\right]=0 \quad (5)$$

After simplification using law of addition, one of the possible of Equation becomes:

$$\frac{6(1-2\mu)(1+c)}{t^2}=-\frac{c(1-\mu)}{a^2}\left(\frac{\partial^2}{\partial R^2}+\frac{1}{\beta^2}\frac{\partial^2}{\partial Q^2}\right) \quad (6)$$

2.2 General Governing Equation

The minimization of energy equation with respect to deflection gives the general governing equation as presented in [25]:

$$\frac{D^*}{2a^2}\int_0^1\int_0^1\left[\frac{6(1-2\mu)(1+c)}{t^2}\left(\frac{\partial^2 w}{\partial R^2}+\frac{1}{\beta^2}.\frac{\partial^2 w}{\partial Q^2}\right)+\frac{(1-\mu)a^2}{t^4}\frac{\partial^2 w}{\partial S^2}-\frac{N_x}{D^*}.\frac{\partial^2 w}{\partial R^2}\right]dR\,dQ=0 \quad (7)$$

Substituting Equation 6 into Equation 7 and simplifying the outcome gives two governing differential equations of a 3-D rectangular plate subject to pure buckling as presented in Equation 8 and 9:

$$\frac{\partial^4 w_1}{\partial R^4}+\frac{2}{\beta^2}.\frac{\partial^4 w_1}{\partial R^2\partial Q^2}+\frac{1}{\beta^4}.\frac{\partial^4 w_1}{\partial Q^4}-\frac{N_{x1}a^4}{gD^*}.\frac{\partial^2 w_1}{\partial R^2}=0 \quad (8)$$

$$\frac{(1-\mu)a^4}{t^4}.\frac{\partial^2 w_S}{\partial S^2}-\frac{N_{xS}a^4}{D^*}.\frac{\partial^2 w_S}{\partial R^2}=0$$

Thus, the trigonometric and polynomial expression for deflection derived from Equation (8) is given in Equation (10a) and (10b) respectively as:

$$w=(a_0+a_1R+a_2\cos g_1R+a_3\sin g_1R)\times(b_0+b_1Q+b_2\cos g_2Q+b_3\sin g_2Q) \quad (10a)$$

$$w=\Delta_0\left(a_0+a_1R+a_2R^2+a_3R^3+a_4R^4\right)\times\left(b_0+b_1Q+b_2Q^2+b_3Q^3+b_4Q^4\right) \quad (10b)$$

Equation (10a) and (10b) can be re-written as:

$$w=A_1h$$

Where:

$$A_1=\Delta_0\begin{bmatrix}a_0\\a_1\\a_2\\a_3\\a_4\end{bmatrix}.\begin{bmatrix}b_0\\b_1\\b_2\\b_3\\b_4\end{bmatrix}$$

$$h=(1\ R\ \cos g_1R\ \sin g_1R)\times(1\ Q\ \cos g_2Q\ \sin g_2Q)$$

$$h=\left[1\ R\ R^2\ R^3\ R^4\right].\left[1\ Q\ Q^2\ Q^3\ Q^4\right] \quad (9)$$

$$\theta_{sx} = \frac{A_2}{a}.\frac{\partial h}{\partial R} \tag{14}$$

$$\theta_{sy} = \frac{A_3}{a\beta}.\frac{\partial h}{\partial Q} \tag{15}$$

Given that: A_1 is the coefficient of deflection A_2 and A_3 are the coefficients of shear deformation in x axis and y axis respectively.

2.3 Direct Governing Equation

By substituting Equations (11), (14) and (15) into Equation (1), the Energy equation becomes:

$$\Pi = \frac{D^*ab}{2a^4}\left[(1-\mu)A_2^2\int_0^1\int_0^1\left(\frac{\partial^2 h}{\partial R^2}\right)^2 dRdQ\ \frac{1}{\beta^2}\left[A_2.A_3 + \frac{(1-2\mu)A_2^2}{2} + \frac{(1-2\mu)A_3^2}{2}\right]\int_0^1\int_0^1\left(\frac{\partial^2 h}{\partial R\partial Q}\right)^2 \right.$$
$$+\frac{(1-\mu)A_3^2}{\beta^4}\int_0^1\int_0^1\left(\frac{\partial^2 h}{\partial Q^2}\right)^2 dRdQ$$
$$+6(1-2\mu)\left(\frac{a}{t}\right)^2\left(\left[A_2^2 + A_1^2 + 2A_1A_2\right].\int_0^1\int_0^1\left(\frac{\partial h}{\partial R}\right)^2 dRdQ\right.$$
$$\left.\left.+\frac{1}{\beta^2}.\left[A_3^2 + A_1^2 + 2A_1A_3\right].\int_0^1\int_0^1\left(\frac{\partial h}{\partial Q}\right)^2 dRdQ\right) - \frac{N_x a^2 A_1^2}{D^*}.\int_0^1\int_0^1\left(\frac{\partial h}{\partial R}\right)^2 dRdQ\right] \tag{16}$$

Differentiating Equation (16) with respect to shear deformation coefficient (A_2 and A_3), and solve simultaneously gives:

$$A_2 = \left(\frac{k_{12}k_{23} - k_{13}k_{22}}{k_{12}k_{12} - k_{11}k_{22}}\right).A_1 \tag{17}$$

$$A_3 = \left(\frac{k_{12}k_{13} - k_{11}k_{23}}{k_{12}k_{12} - k_{11}k_{22}}\right).A_1 \tag{18}$$

Let:

$$k_{11} = (1-\mu)k_{RR} + \frac{1}{2\beta^2}(1-2\mu)k_{RQ} + 6(1-2\mu)\left(\frac{a}{t}\right)^2 k_R \tag{19}$$

$$k_{21} = k_{12} = \frac{1}{2\beta^2}k_{RQ};\ k_{13} = -6(1-2\mu)\left(\frac{a}{t}\right)^2 k_R;\ k_{32} = k_{23} = -\frac{6}{\beta^2}(1-2\mu)\left(\frac{a}{t}\right)^2 k_Q \tag{20}$$

$$k_{22} = \frac{(1-\mu)}{\beta^4}k_{QQ} + \frac{1}{2\beta^2}(1-2\mu)k_{RQ} + \frac{6}{\beta^2}(1-2\mu)\left(\frac{a}{t}\right)^2 k_Q \tag{21}$$

Where:

$$k_{RR} = \int_0^1\int_0^1\left(\frac{\partial^2 h}{\partial R^2}\right)^2 dRdQ \tag{22}$$

$$k_{RQ} = \int_0^1\int_0^1\left(\frac{\partial^2 h}{\partial R\partial Q}\right)^2 dRdQ \tag{23}$$

$$k_{QQ} = \int_0^1\int_0^1\left(\frac{\partial^2 h}{\partial Q^2}\right)^2 dRdQ \tag{24}$$

$$k_R = \int_0^1 \int_0^1 \left(\frac{\partial h}{\partial R}\right)^2 dRdQ \quad (25)$$

$$k_Q = \int_0^1 \int_0^1 \left(\frac{\partial h}{\partial Q}\right)^2 dRdQ \quad (26)$$

Differentiating Equation (16) with respect to deflection coefficient (A_1) and simplifying the outcome, an expression for the critical buckling load (N_{xcr}) is established as:

$$\frac{N_x a^2}{D^*} = 6(1-2\mu)\left(\frac{a}{t}\right)^2 \left(\left[1+\left(\frac{k_{12}k_{23}-k_{13}k_{22}}{k_{12}k_{12}-k_{11}k_{22}}\right)\right] + \frac{1}{\beta^2}.\left[1+\left(\frac{k_{12}k_{13}-k_{11}k_{23}}{k_{12}k_{12}-k_{11}k_{22}}\right)\right].\frac{k_Q}{k_R}\right) \quad (27)$$

Similarly:

$$N_{xcr} = \frac{(1+\mu)Et^3}{2a^2}\left(\frac{a}{t}\right)^2 \left(\left[1+\left(\frac{k_{12}k_{23}-k_{13}k_{22}}{k_{12}k_{12}-k_{11}k_{22}}\right)\right] + \frac{1}{\beta^2}.\left[1+\left(\frac{k_{12}k_{13}-k_{11}k_{23}}{k_{12}k_{12}-k_{11}k_{22}}\right)\right].\frac{k_Q}{k_R}\right) \quad (28)$$

2.4 Numerical Analysis

A problem of a clamped rectangular thick plate uniaxial compressive load is presented. The trigonometric and polynomial displacement function as presented in the Equation (10a) and (10b) was applied to determine the value of the critical buckling load in the plate at various aspect ratios.

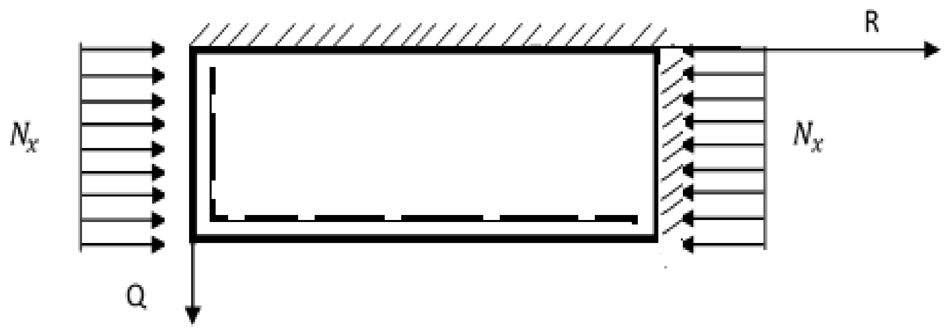

Figure 2: CCSS Rectangular Plate subjected to uniaxial compressive load

The boundary conditions of the plate in figure 3 are as follows:

At $R = Q = 0$; deflection $(w) = 0$ (29)

At $R = Q = 0$; slope $\left(\frac{dw}{dR} = \frac{dw}{dQ}\right) = 0$ (30)

At $R = Q = 1$; deflection $(w) = 0$ (31)

At $R = Q = 1$; bending moment $\left(\frac{d^2w}{dR^2} = \frac{d^2w}{dQ^2}\right) = 0$ (32)

Substituting Equation (29) to (32) into the derivatives of w and solving gave the characteristic equation as:

$2Cos\, g_1 + g_1 Sin\, g_1 - 2$

The value of g_1 that satisfies Equation (33) is:

$g_1 = 2m\pi$ [$where\ m = 1, 2, 3 \ldots$]

Substituting Equation (34) into the derivatives of w and satisfying the boundary conditions of Equation (29) to (32) gives the following constants:

$$a_0 = g_1 a_3;\ a_1 = -g_1 a_3;\ b_0 = g_1 b_3;\ b_0 = -g_1 b_3 \quad (35)$$

Substituting the constants of Equation (34) and (35) into Equation (10a) and simplify the outcome gives:

$$w = a_3 \times b_3 (\ g_1 - g_1 R - g_1 Cos\ g_1 R + Sin\ g_1 R).(\ g_1 - g_1 Q - g_1 Cos\ g_1 Q + Sin\ g_1 Q) \quad (36)$$

Let the amplitude,

$$A_1 = a_3 \times b_3 \quad (37)$$

And;

$$h = (\ g_1 - g_1 R - g_1 Cos\ g_1 R + Sin\ g_1 R).(\ g_1 - g_1 Q - g_1 Cos\ g_1 Q + Sin\ g_1 Q) \quad (38)$$

Thus, the trigonometric deflection functions after satisfying the boundary conditions is:

$$w = A_1 (\ g_1 - g_1 R - g_1 Cos\ g_1 R + Sin\ g_1 R).(\ g_1 - g_1 Q - g_1 Cos\ g_1 Q + Sin\ g_1 Q) \quad (39)$$

Similarly, substituting Equations (29 to 32) into Equation (10b) and solving gives the following constants:

$$a_0 = 0;\ a_1 = 0;\ a_2 = 1.5 a_4;\ a_3 = 2.5 a_4 and \quad (40)$$

$$b_0 = 0;\ b_1 = 0;\ b_2 = 1.5 b_4;\ b_3 = 2.5 b_4 \quad (41)$$

Substituting the constants of Equation (40) and (41) into Equation (10b) gives;

$$w = (1.5 a_4 R^2 - 2.5 a_4 R^3 + a_4 R^4) \times (1.5 b_4 Q^2 - 2.5 b_4 Q^3 + b_4 Q^4) \quad (42)$$

Simplifying Equation (42) which satisfying the boundary conditions of Equation (29 to 32) gives:

$$w = a_4 \times b_4 (1.5 R^2 - 2.5 R^3 + R^4) \times (1.5 Q^2 - 2.5 Q^3 + Q^4) \quad (43)$$

Let the amplitude,

$$A_1 = a_4 \times b_4 \quad (44)$$

And;

$$h = (1.5 R^2 - 2.5 R^3 + R^4) \times (1.5 Q^2 - 2.5 Q^3 + Q^4) \quad (45)$$

Thus, the polynomial deflection functions after satisfying the boundary conditions is:

$$w = (1.5 R^2 - 2.5 R^3 + R^4) \times (1.5 Q^2 - 2.5 Q^3 + Q^4). A_1 \quad (46)$$

3.0 RESULTS AND DISCUSSIONS

The numerical values of the stiffness for a CCSS plate were obtained using Equation (22) to (26) by applying the two-shape function (trigonometric and polynomial) as obtained in Equation 38 and 45 and their results are presented in Table 1.

The numerical value of critical buckling load is determined by applying its expression obtained in Equation (27) and (28) appropriately. The non-dimensional trigonometric form of the critical buckling load for an isotropic CCSS plate clamped in the two opposite edges and the other edges simply supported under uniaxial compressive load at varying aspect ratio is presented in Table 2 and 3. The polynomial form of the buckling load is contained in the tables 4 and 5. A numerical and graphical comparison was made between the two approaches (trigonometric and polynomial shear deformation functions) use for the study of CCSS thick plate at different sizes and thickness of the plate as presented in Table 6 and Figure 3 to 11.

The values obtained in Table 2, 3, 4 and 5, shows that as the values of critical buckling load increase, the span- thickness ratio increases. This reveals that as the in-plane load on the plate increase and approaches the critical buckling, the failure in a plate structure is a bound to occur. This means that a decrease in the thickness of the plate, increases the chance of failure in a plate structure. Hence, failure tendency in the plate structure can be mitigated by increasing its thickness.

It is also observed in the table that as the value of critical buckling load decreases, the length to breadth ratio increases while as critical buckling load increases, the length to breadth ratio increases. This implies that an increase in plate width increases the chance of failure in a plate structure. It can be deduced that as the in-plane load which will cause the plate to fail by compression increases from zero to critical buckling load (, the buckling of the plate exceeds specified elastic limit thereby causing failure in the plate structure. This means that, the load that causes the plate to deform also causes the plate material to buckle simultaneously.

The comparison shows that the value of the critical buckling load using polynomial is higher than that of trigonometric functions. This is quite expected because the trigonometric function gives higher value of stiffness coefficient is than polynomial, and therefore considers safer to use in the thick plate analysis.

The percentage difference of critical buckling load between the present study using polynomial, and that of trigonometric function for an isotropic rectangular thick plate clamped at the two opposite sides of the plate and the other side simply support subjected to a uniaxial compression at varying aspect ratio is presented in table 6 and figures 3 to 11. It was discovered that the values of percentage error increase as the span to thickness ratio of the plate increases, the percentage differences between the two approaches reduce as the span to thickness ratio reduces. This means that as the pate gets thinner, the two methods differs more and becomes close as the plate gets thick. This shows the high level of simplicity and logicality using this theory. Furthermore, the degree of the error in percentage increases as the length to breadth ratio decreases. This means that the length of the plate widens, the two approaches become the same.

In summary, the overall average percentage differences between the two functions recorded is 3.8%. This value has been so small (less than 5%) is quite acceptable in statistical analysis as it will not put the structure into danger. This means that at about 96% confidence both approaches are the same and can be applied with confidence for analysis of plate of any thickness. Thus, the present model has some level safety and can be used with confidence for buckling analysis of CCSS thick plate.

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Table 1: The polynomial and trigonometric stiffness coefficients of deflection function of the CCSS plate

Displacement Shape Function	k_{RR}	k_{RQ}	k_{QQ}	k_R	k_Q
Polynomial	0.01357	0.00735	0.01357	0.000065	0.000065
Trigonometric	79, 207.0	42, 328.3	79, 207.0	3, 921.10	3, 921.10

Table 2: Non-dimensional Critical Buckling Load $\frac{N_x a^2}{\pi^2 D}$ on the CCSS Rectangular Plate Using Trigonometric Function

	$N_{xcr} = \frac{N_x a^2}{\pi^2 D}$								
$\propto = \frac{a}{t}$	$\beta = 1.0$	$\beta = 1.5$	$\beta = 2.0$	$\beta = 2.5$	$\beta = 3.0$	$\beta = 3.5$	$\beta = 4.0$	$\beta = 4.5$	$\beta = 5.0$
4	4.7605	2.8135	2.2833	2.0706	1.9646	1.9040	1.8661	1.8407	1.8229
5	5.3941	3.1154	2.5131	2.2738	2.1550	2.0873	2.0449	2.0167	1.9968
10	6.5579	3.6363	2.9031	2.6166	2.4753	2.3950	2.3448	2.3113	2.2878
15	6.8308	3.7526	2.9891	2.6919	2.5454	2.4622	2.4103	2.3756	2.3513
20	6.9318	3.7951	3.0204	2.7192	2.5709	2.4866	2.4341	2.3990	2.3743
30	7.0057	3.8260	3.0432	2.7391	2.5894	2.5044	2.4513	2.4159	2.3911
40	7.0320	3.8370	3.0513	2.7462	2.5960	2.5107	2.4575	2.4219	2.3970
50	7.0442	3.8421	3.0550	2.7494	2.5990	2.5136	2.4603	2.4247	2.3998
60	7.0509	3.8448	3.0571	2.7512	2.6006	2.5152	2.4618	2.4262	2.4013
70	7.0549	3.8465	3.0583	2.7523	2.6016	2.5161	2.4628	2.4272	2.4022
80	7.0575	3.8476	3.0591	2.7530	2.6023	2.5168	2.4634	2.4277	2.4028
90	7.0593	3.8483	3.0596	2.7534	2.6027	2.5172	2.4638	2.4282	2.4032
100	7.0606	3.8489	3.0600	2.7538	2.6031	2.5175	2.4641	2.4284	2.4034
1000	7.0660	3.8511	3.0617	2.7552	2.6044	2.5188	2.4653	2.4297	2.4047
1500	7.0660	3.8511	3.0617	2.7552	2.6044	2.5188	2.4653	2.4297	2.4047

Table 3: Non-dimensional Critical Buckling Load $\frac{N_x a^2}{E t^3}$ on the CCSS Rectangular Plate Using Trigonometric Function

	$N_{xcr} = \frac{N_x a^2}{E t^3}$								
$\propto = \frac{a}{t}$	$\beta = 1.0$	$\beta = 1.5$	$\beta = 2.0$	$\beta = 2.5$	$\beta = 3.0$	$\beta = 3.5$	$\beta = 4.0$	$\beta = 4.5$	$\beta = 5.0$
4	4.1764	2.4683	2.0031	1.8165	1.7235	1.6704	1.6371	1.6149	1.5993
5	4.7323	2.7332	2.2047	1.9948	1.8906	1.8312	1.7940	1.7692	1.7518
10	5.7532	3.1901	2.5469	2.2956	2.1716	2.1011	2.0571	2.0277	2.0071
15	5.9927	3.2921	2.6223	2.3616	2.2331	2.1601	2.1145	2.0841	2.0628
20	6.0812	3.3294	2.6498	2.3856	2.2554	2.1815	2.1354	2.1046	2.0830
30	6.1461	3.3566	2.6698	2.4030	2.2717	2.1971	2.1506	2.1195	2.0977
40	6.1692	3.3662	2.6769	2.4092	2.2774	2.2026	2.1559	2.1248	2.1029
50	6.1799	3.3706	2.6802	2.4121	2.2801	2.2052	2.1584	2.1272	2.1053
60	6.1857	3.3731	2.6820	2.4136	2.2815	2.2066	2.1598	2.1285	2.1066
70	6.1893	3.3745	2.6830	2.4146	2.2824	2.2074	2.1606	2.1293	2.1074

80	6.1915	3.3755	2.6837	2.4152	2.2830	2.2079	2.1611	2.1299	2.1079
90	6.1931	3.3761	2.6842	2.4156	2.2834	2.2083	2.1615	2.1302	2.1083
100	6.1942	3.3766	2.6846	2.4159	2.2837	2.2086	2.1617	2.1305	2.1085
1000	6.1990	3.3786	2.6860	2.4172	2.2848	2.2097	2.1628	2.1316	2.1096
1500	6.1990	3.3786	2.6860	2.4172	2.2848	2.2097	2.1628	2.1316	2.1096

Table 4: Non-dimensional Critical Buckling Load $\frac{N_x a^2}{\pi^2 D}$ on the CCSS Rectangular Plate Using Polynomial Function

	$N_{xcr} = \frac{N_x a^2}{\pi^2 D}$								
$\propto = \frac{a}{t}$	$\beta = 1.0$	$\beta = 1.5$	$\beta = 2.0$	$\beta = 2.5$	$\beta = 3.0$	$\beta = 3.5$	$\beta = 4.0$	$\beta = 4.5$	$\beta = 5.0$
4	4.9006	2.9021	2.3550	2.1349	2.0250	1.9621	1.9228	1.8965	1.8780
5	5.5747	3.2242	2.6000	2.3514	2.2278	2.1573	2.1132	2.0837	2.0630
10	6.8267	3.7852	3.0194	2.7197	2.5716	2.4874	2.4348	2.3997	2.3751
15	7.1229	3.9113	3.1125	2.8010	2.6474	2.5600	2.5055	2.4691	2.4435
20	7.2328	3.9574	3.1465	2.8306	2.6749	2.5864	2.5312	2.4943	2.4684
30	7.3134	3.9911	3.1712	2.8522	2.6950	2.6057	2.5499	2.5127	2.4865
40	7.3420	4.0030	3.1799	2.8598	2.7021	2.6124	2.5565	2.5191	2.4929
50	7.3553	4.0085	3.1840	2.8633	2.7054	2.6156	2.5596	2.5222	2.4959
60	7.3626	4.0115	3.1862	2.8653	2.7071	2.6173	2.5612	2.5238	2.4975
70	7.3669	4.0134	3.1875	2.8664	2.7082	2.6184	2.5622	2.5248	2.4985
80	7.3698	4.0145	3.1884	2.8672	2.7089	2.6190	2.5629	2.5254	2.4991
90	7.3718	4.0154	3.1890	2.8677	2.7094	2.6195	2.5634	2.5259	2.4996
100	7.3731	4.0159	3.1894	2.8681	2.7098	2.6198	2.5637	2.5262	2.4999
1000	7.3791	4.0184	3.1912	2.8696	2.7112	2.6212	2.5650	2.5275	2.5012
1500	7.3791	4.0184	3.1912	2.8697	2.7112	2.6212	2.5650	2.5275	2.5012

Table 5: Non-dimensional Critical Buckling Load $\frac{N_x a^2}{Et^3}$ on the CCSS Rectangular Plate Using Polynomial Function

	$N_{xcr} = \frac{N_x a^2}{Et^3}$								
$\propto = \frac{a}{t}$	$\beta = 1.0$	$\beta = 1.5$	$\beta = 2.0$	$\beta = 2.5$	$\beta = 3.0$	$\beta = 3.5$	$\beta = 4.0$	$\beta = 4.5$	$\beta = 5.0$
4	4.2993	2.5460	2.0660	1.8729	1.7765	1.7214	1.6869	1.6638	1.6476
5	4.8907	2.8286	2.2809	2.0629	1.9545	1.8926	1.8539	1.8280	1.8099
10	5.9890	3.3207	2.6489	2.3860	2.2561	2.1822	2.1361	2.1053	2.0836
15	6.2489	3.4313	2.7306	2.4573	2.3225	2.2459	2.1981	2.1661	2.1437
20	6.3453	3.4718	2.7604	2.4833	2.3467	2.2691	2.2206	2.1883	2.1655
30	6.4160	3.5014	2.7821	2.5022	2.3643	2.2859	2.2370	2.2044	2.1814
40	6.4411	3.5118	2.7897	2.5089	2.3705	2.2919	2.2428	2.2100	2.1870
50	6.4528	3.5167	2.7933	2.512	2.3734	2.2947	2.2455	2.2127	2.1897

60	6.4592	3.5193	2.7953	2.5137	2.3750	2.2962	2.2470	2.2141	2.1911
70	6.4630	3.5209	2.7964	2.5147	2.3759	2.2971	2.2479	2.2150	2.1919
80	6.4655	3.5219	2.7972	2.5154	2.3765	2.2977	2.2484	2.2156	2.1925
90	6.4672	3.5227	2.7977	2.5158	2.3770	2.2981	2.2488	2.2159	2.1929
100	6.4684	3.5232	2.7981	2.5162	2.3773	2.2984	2.2491	2.2162	2.1931
1000	6.4736	3.5253	2.7997	2.5175	2.3785	2.2996	2.2503	2.2174	2.1943
1500	6.4737	3.5253	2.7997	2.5175	2.3786	2.2996	2.2503	2.2174	2.1943

Table 6: Percentage difference of Buckling Load on the CCSS Rectangular Plate between Polynomial and trigonometric Approach

	Average Percentage Difference %								
$\propto = \frac{a}{t}$	$\beta = 1.0$	$\beta = 1.5$	$\beta = 2.0$	$\beta = 2.5$	$\beta = 3.0$	$\beta = 3.5$	$\beta = 4.0$	$\beta = 4.5$	$\beta = 5.0$
4	2.8582	3.0513	3.0423	3.0104	2.9837	2.9640	2.9498	2.9393	2.9315
5	3.2386	3.3747	3.3425	3.3002	3.2682	3.2455	3.2293	3.2176	3.2089
10	3.9373	3.9325	3.8521	3.7893	3.7467	3.7180	3.6980	3.6837	3.6732
15	4.1011	4.0571	3.9645	3.8966	3.8515	3.8213	3.8004	3.7855	3.7745
20	4.1618	4.1026	4.0054	3.9356	3.8896	3.8588	3.8376	3.8224	3.8113
30	4.2062	4.1357	4.0352	3.9640	3.9173	3.8861	3.8646	3.8493	3.8380
40	4.2219	4.1474	4.0457	3.9740	3.9270	3.8957	3.8742	3.8588	3.8475
50	4.2293	4.1529	4.0506	3.9787	3.9316	3.9002	3.8786	3.8632	3.8519
60	4.2333	4.1558	4.0532	3.9812	3.9341	3.9027	3.8810	3.8656	3.8543
70	4.2357	4.1576	4.0549	3.9828	3.9356	3.9041	3.8825	3.8670	3.8557
80	4.2372	4.1588	4.0559	3.9838	3.9365	3.9051	3.8834	3.8680	3.8566
90	4.2383	4.1596	4.0566	3.9844	3.9372	3.9057	3.8841	3.8686	3.8573
100	4.2391	4.1602	4.0571	3.9849	3.9377	3.9062	3.8845	3.8691	3.8577
1000	4.2423	4.1626	4.0593	3.9870	3.9397	3.9082	3.8865	3.8710	3.8597
1500	4.2424	4.1626	4.0593	3.9870	3.9397	3.9082	3.8865	3.8710	3.8597
Average % difference	4.0415	4.0048	3.9156	3.8493	3.8051	3.7753	3.7547	3.74	3.7292
Total Average % difference	3.8462								

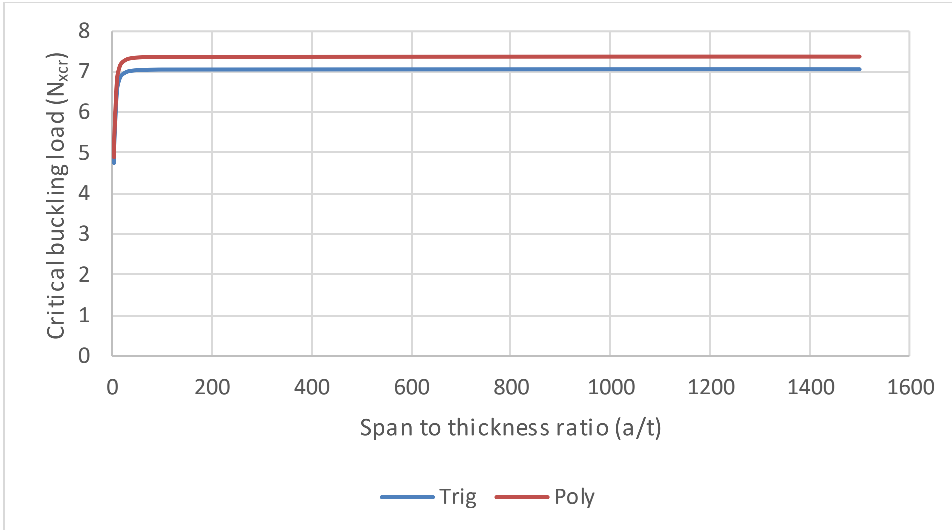

Figure 3: Graph of Critical buckling load (N_{xcr}) versus aspect ratio (a/t) of a square rectangular plate

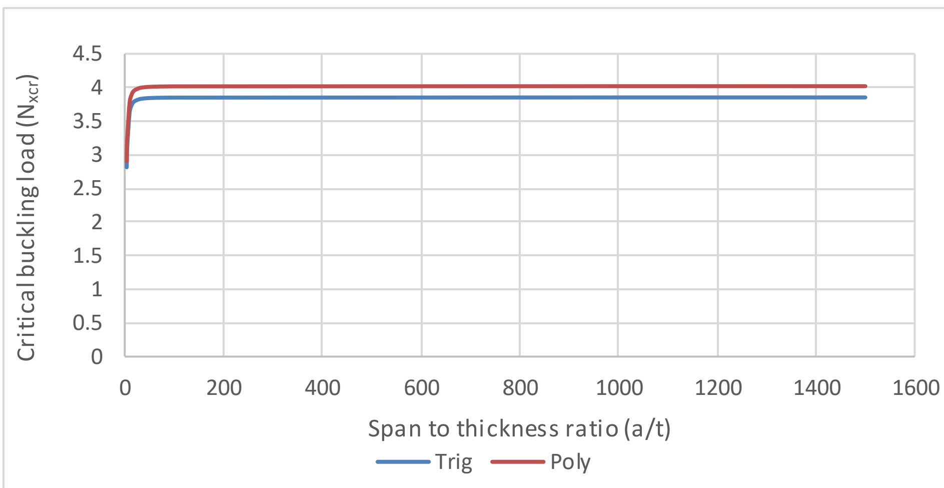

Figure 4: Graph of Critical buckling load (N_{xcr}) versus aspect ratio (a/t) of a rectangular plate with length to width ratio of 1.5.

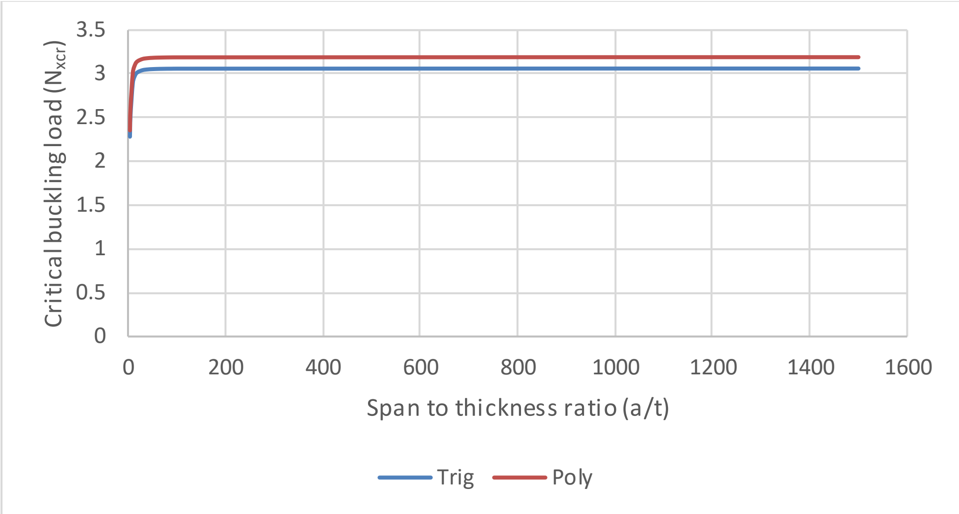

Figure 5: Graph of Critical buckling load (N_{xcr}) versus aspect ratio (a/t) of a rectangular plate with length to width ratio of 2.0

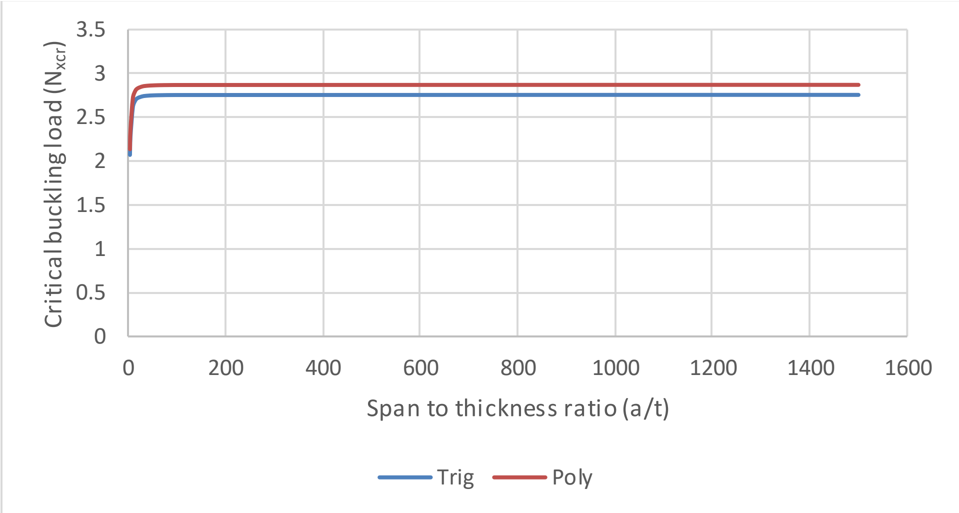

Figure 6: Graph of Critical buckling load (N_{xcr}) versus aspect ratio (a/t) of a rectangular plate with length to width ratio of 2.5

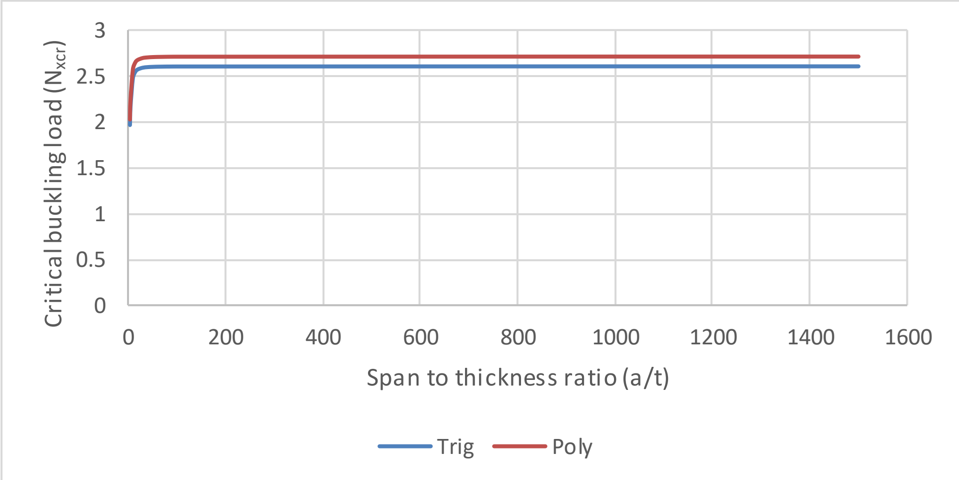

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Figure 7: Graph of Critical buckling load (N_{xcr}) versus aspect ratio (a/t) of a rectangular plate with length to width ratio of 3.0

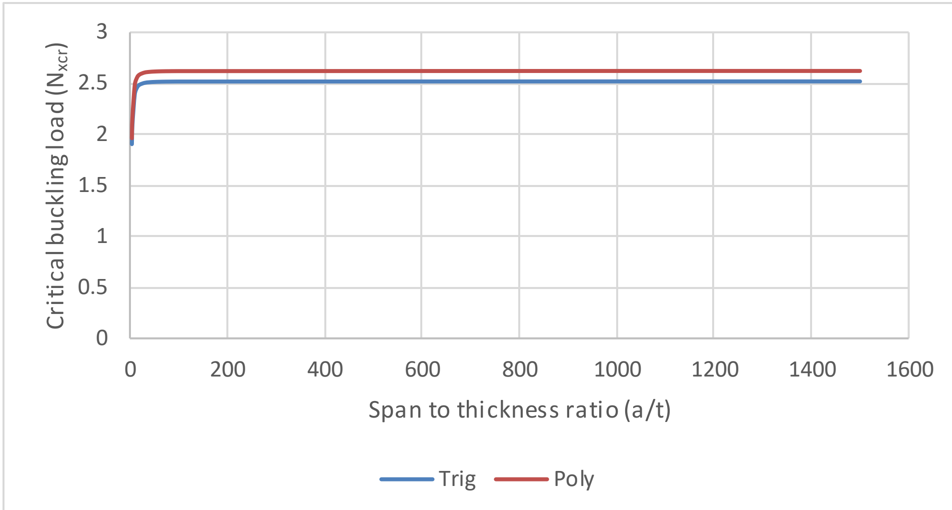

Figure 8: Graph of Critical buckling load (N_{xcr}) versus aspect ratio (a/t) of a rectangular plate with length to width ratio of 3.5

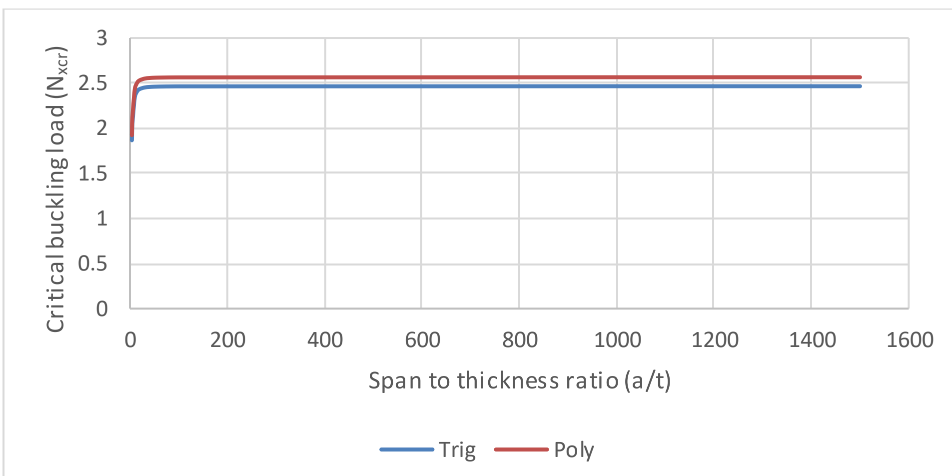

Figure 9: Graph of Critical buckling load (N_{xcr}) versus aspect ratio (a/t) of a rectangular plate with length to width ratio of 4.0

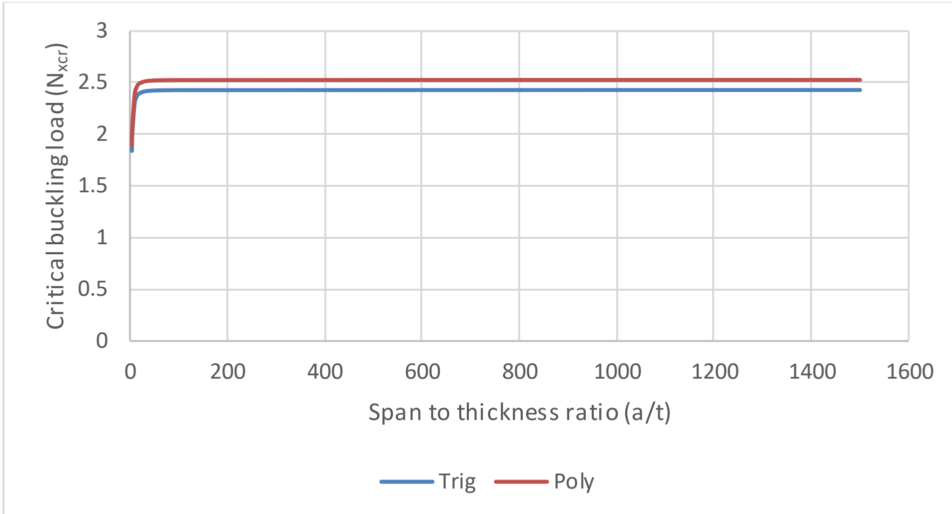

Figure 10: Graph of Critical buckling load (N_{xcr}) versus aspect ratio (a/t) of a rectangular plate with length to width ratio of 4.5

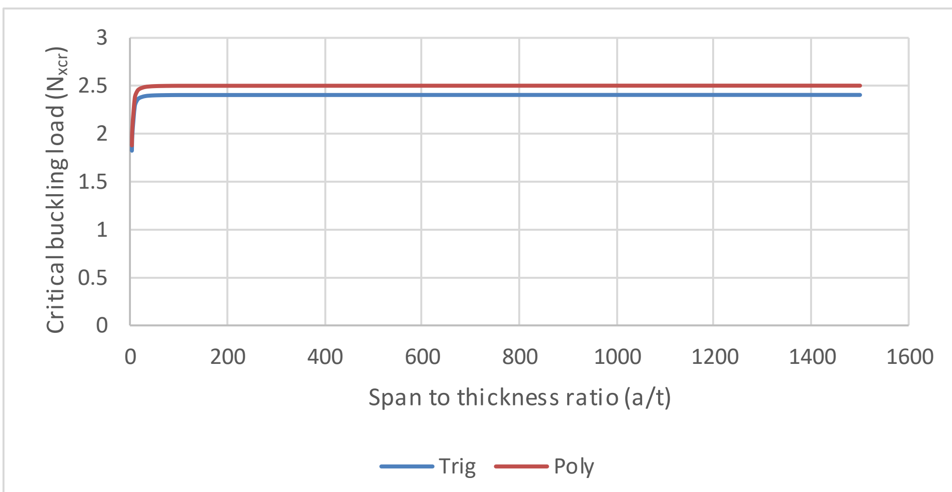

Figure 11: Graph of Critical buckling load (N_{xcr}) versus aspect ratio (a/t) of a rectangular plate with length to width ratio of 5.0

4.0 CONCLUSION AND RECOMMENDATION

From the result obtained in this study, it is observed that CPT and gives reliable results in thin plates, but over-predicts buckling loads in relatively thick plates. Also, the RPT gives is an approximate relation for buckling analysis of thick plate, whereas 3-D theory yields an exact solution. This proved that the displacement functions (polynomial and trigonometric) developed in this work are recommended for the thick plate analysis.

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