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Large Deflection Analysis of Clamped Thin Rectangular Isotropic Plate under the Action of a Uniform Distributed Load

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Abstract

This present paper deals with large deflection of clamped thin rectangular isotropic plate under uniformly distributed load. The analysis of clamped plates is of great important and its structural behavior has not been completely understood. Previous studies have made a great in road in the analysis of clamped plates through varied approaches mostly assuming trigonometric series as displacement field. A variational method based on the principle of minimization of total potential energy has been employed through assumed displacement field. Therefore, the von Karman differential equation was decoupled through direct integration retaining its non linear character. The aim of this present studies is to provide solution to analysis structural behavior of clamped (CCCC) thin rectangular isotropic plate under uniform distributed. The analysis was accomplished through a theoretical formulation of shape function based on polynomial series and subsequently, the formulated shape function was used on Ritz energy method. The resulting functional was minimized to obtain a general amplitude equation of the form $K_1\Delta^3+K_2\Delta+K_3$. Where K_1, K_2 and K_3 are coefficients of amplitude equation and Δ is the deflection coefficient (factor). Newton-Raphson method was used to evaluate the deflection coefficient. Values of Δ from Timoshenko and that from present study were compared with an aspect ratios ranging from 1.0 to 1.5 with an increment of 0.1. From results obtained, the average percentage difference for the pervious and present studies is 3.7646%, The percentage difference for the plate was within acceptable limit of 0.05 or 5% level of significance in statistics. It is shown from the comparison that good agreement exists between the present and previous works and that this approach provides simply, direct, straightforward and highly accurate solutions for this family of problems.

Keywords: Nonlinear Analysis, Functional, Ritz Methods, Variational Principles, Minimization, Boundary conditions, Large deflection.

1. INTRODUCTION

Thin plates are extensively used in many aspect of human endeavour particularly, in civil, mechanical, aeronautical engineering. They are mostly subjected to uniform pressure loading in its transverse faces [1]. Because of these wide applications in the practical fieid, its analysis has become of a great important. It is paramount need to check the geometry of the plate and its support, the behaviour of the material used and the type of loads, and their way of application [2]. Analysis of thin plates subjected to transverse loads is often realized by using linear theory in which one assumes that the lateral displacements or deflections due to the loads are small in comparison to is dimensions. The loads in this case are carried by bending action of the plate only. This theory neglects the deformation of the middle surface and it's corresponding in plane force [3]. As deflections of the plate become large, the deformations in the middle surface of the plate increase in such a manner that errors in solutions using linear theory grows simultaneously [4]. These errors become so large that linear solution containing displacements and stresses totally disagree with experimental data. Thus, the three nonlinear equations as developed by von Karman are used for the analysis of thin plates.

The solution of tin rectangular plate clamped on its four edges and subjected to a uniformly distributed load is of great importance and has been a subject of study. Many authors have made an inroad in calculating deflections of uniformly loaded rectangular plates fixed all-round. These authors used different methods in accomplishing their analysis. Most of the available solutions are approximate methods. The accuracy of the analytic solutions for thin rectangular plate developed in the literature through this method varies. No accurate results appear to be available [5]. The major method of approach used in calculating the solution of the maximum deflection for clamped thin rectangular plate under the action of uniform load is Trigonometric series.

Imrak and Gerdemeli [5] presented an exact solution for thin rectangular plate in which each term of the serried is trigonometric and hyperbolic. Chaurasia and Jagdish [6] calculated the large deflection and bending stresses for clamped circular plate under non-uniform load by using berge's approximate method. Silveira and Albuquerque [7] used boundary element method to obtain the large deflection of composite laminate thin square plates clamped on the four edges. Vanam *et al.,* [8] carried out static analysis of an isotropic rectangular plate for CCCC and SSSS. Osadebe and Aginam [9] developed Ritz mathematical and variational method and applied it in the analysis of uniformly loaded clamped isotropic rectangular plate. Ibearugbulem *et al.,* [10] worked on plastic buckling analysis of thin rectangular isotropic plate under uniform in-plane compression in the longitudinal direction. They used Taylor's series to approximate the displacement function for CCCC plate. Ezeh *et al.,* [11] used Galerkin's indirect variation method in analysis elastic stability of thin rectangular plate clamped on all edges.

This paper analyses the deflections of a rectangular clamped thin plate under the action of uniformly distributed loads. A comprehensive approach for the numerical solution of thin rectangular isotropic plate problem under uniformly distributed loads, clamped on the four edges and boundary conditions is presented. A solution and direct integration of von Karman governing differential equation in terms of polynomial function is given and Poisson ratio (v) of 0.3 was used. The numerical values obtained by previous researchers were compared with the values obtained by present study and there is a reasonable correlation and agreement between the results. The application of present approach is simple, direct and straightforward.

2. NONLINEAR PLATE THEORY

$$\frac{\partial^4\phi}{\partial x^4}+\frac{2\partial^4\phi}{\partial x^2\partial y^2}+\frac{\partial^4\phi}{\partial y^2}=E\left[\left(\frac{\partial^2 w}{\partial x\partial y}\right)^2-\frac{\partial^2 w}{\partial x^2}\frac{\partial^2 w}{\partial y^2}\right] \quad \ldots\ldots 1$$

$$\frac{\partial^4 w}{\partial x^4}+\frac{2\partial^4 w}{\partial x^2\partial y^2}+\frac{\partial^4 w}{\partial y^4}=\frac{1}{D}\left[q+h\left(\frac{\partial^2\phi}{\partial y^2}\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2\phi}{\partial x^2}\frac{\partial^2 w}{\partial y^2}-\frac{2\partial^2\phi}{\partial x\partial y}\frac{\partial^2 w}{\partial x\partial y}\right)\right] \quad \ldots\ldots 2$$

Equations 1 and 2 define a system of nonlinear, partial differential equations, and they are referred to as the governing differential equations for large deflections theory of plates. The first equation can be described as compatibility equation and, describing the second equation in the same tone as equilibrium equation.

$$\frac{\partial^4\phi}{\propto^4\partial R^4}+\frac{2\partial^4\phi}{\propto^2\partial R^2\partial Q^2}+\frac{\partial^4\phi}{\partial Q^4}=\frac{E}{\propto^2}\left(\left(\frac{\partial^2 w}{\partial R\,\partial Q}\right)^2-\frac{\partial^2 w}{\partial R^2}\frac{\partial^2 w}{\partial Q^2}\right) \quad \ldots\ldots 3$$

$$\frac{\partial^4 w}{\propto^4\partial R^4}+\frac{2\partial^4 w}{\propto^2\partial R^2\partial Q^2}+\frac{\partial^4 w}{\partial Q^4}=\frac{qb^4}{D}+\frac{h}{\propto^2 D}\left(\frac{\partial^2\phi}{\partial Q^2}\frac{\partial^2 w}{\partial R^2}+\frac{\partial^2\phi}{\partial R^2}\frac{\partial^2 w}{\partial Q^2}-\frac{2\partial^2\phi}{\partial R\,\partial Q}\frac{\partial^2 w}{\partial R\,\partial Q}\right) \quad \ldots\ldots 4$$

Equations 3 and 4 are nonlinear differential equation for large deflection of plate under normal load represented in non-dimensional axes.

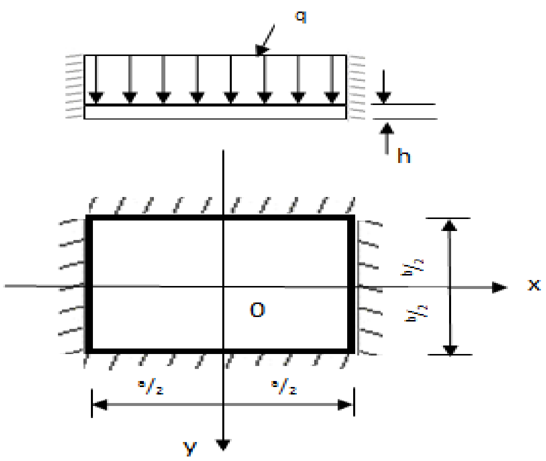

Figure 1: Typical Rectangular Plate Uniformly Loaded and Clamped at Four Edges (CCCC)

3. SHAPE FUNCTION

Assuming a displacement function of:

$W = w(x,y)\sum_{m=0}^{\infty}\sum_{n=0}^{\infty} P_m B_n x^m y^n$ …………………….. 5

Displacement functions in Equation 5 was expressed in terms of non-dimensional parameters (Q and R).

Recall that.

X = aR, and y = Bq …………………………………..6

Substituting Equation 6 into Equation 5 and terminating the series at m = n = 4 gave

$W = W(R,Q) = \sum_{m=0}^{\infty}\sum_{n=0}^{\infty} P_m B_n a^m R^m b^n Q^n$ …. 7

$Let\ a_m = P_m a^m$ and $b_n = B_n b^n$ …………………... 8

Thus:

$W = W(R,Q) = \sum_{m=0}^{4}\sum_{n=0}^{4} a_m R^m b_n Q^n$ ………. 9

Expanding Equation 9 to 4th series over two bases, one in the x-direction and the other in y-direction and normalizing the function by makes the denominator equal to one gave:

$W(a_iR, b_iQ) = (a_0 + a_1R + a_2R^2 + a_3R^3 + a_4R^4)(b_0 + b_1Q + b_2Q^2 + b_3Q^3 + b_4Q^4)$ …………………………….. 10

Equation 10 gives polynomial approximation of the shape function. With the proper use of the boundary conditions of the plate, the deflection of the plate will be adequately defined.

4. BOUNDARY CONDITION

W(R) = 0; W (Q) = 0 when R = 0 and R = 1;

W′(R) = 0; W (Q) = 0 when R = 0 and R = 1

Applying these boundary conditions on Equation 10 gave the displacement functions:

For CC: $a_4(R^2 - 2R^3 + R^4)$ (R-direction)

For CC: $b_4(Q^2 - 2Q^3 + Q^4)$ (Q-direction)

Multiplying these displacement functions together gave:

$CCCC = a_4(R^2 - 2R^3 + R^4)\, b_4(Q^2 - 2Q^3 + Q^4)$ ……. 11

Factorizing Equation 11 and letting a_4b_4 be equal to Δ gave:

$w = \Delta(R^2 - 2R^3 + R^4)(Q^2 - 2Q^3 + Q^4)$ …………..… 12

Enem (2018) established particular stress function for SSSS thin rectangular isotropic plate by substituting shape function into von Karman compatibility equation and the resultant is given as

$$\emptyset_{CCCC} = \frac{\beta\Delta^2}{6350400}[(28R^6 - 72R^7 + 78R^8 - 40R^9 + 8R^{10})(28Q^6 - 72Q^7 + 78Q^8 - 40Q^9 + 8Q^{10}) - (14R^6 - 48R^7 + 57R^8 - 30R^9 + 6R^{10})(14Q^6 - 48Q^7 + 57Q^8 - 30Q^9 + 6Q^{10})] \quad \ldots 13$$

β in Equation 13 represents $\frac{E}{\alpha^2\left(\frac{1}{\alpha^4}+\frac{2}{\alpha^2}+1\right)}$

5. NON-LINEAR TOTAL POTENTIAL ENERGY

Equation 4 was considered as a functional expressing total potential energy, π of a deformed elastic body and load acting on it. Equation 4 therefore, consists of potential energy of internal forces and potential energy of external forces. However, potential energy of a body is a measure of work done by external and internal forces in moving the body from its initial position to a final one and it will be observed that all the terms in Equation 4 are in form of forces. Equation 4 was therefore converted to full potential energy by multiplying all the terms in it by displacement, *w*, hence:

$$\pi = \frac{1}{2}\int_0^1\int_0^1\left(\frac{\partial^4 w}{\alpha^4\partial R^4}.w + \frac{2\partial^4 w}{\alpha^2\partial R^2\partial Q^2}.w + \frac{\partial^4 w}{\partial Q^4}.w\right)\partial R\partial Q - \frac{1}{D}\int_0^1\int_0^1\left[qb^4.w + \frac{h}{2\alpha^2}\left(\frac{\partial^2\phi}{\partial Q^2}\frac{\partial^2 w}{\partial R^2}.w + \frac{\partial^2\phi}{\partial R^2}\frac{2\partial^2 w}{\partial Q^2}.w - \frac{2\partial^2\phi}{\partial R\partial Q}.\frac{\partial^2 w}{\partial R\partial Q}.w\right)\right]\partial R\partial Q \quad \ldots 14$$

Letting $w = \Delta H_1$ and $\emptyset = \Delta^2 H_2$

Where Δ is the deflection coefficient of the plate. H_1 and H_2 are the profiles of the deflection and stress function respectively. Substituting for *w* and ∅ into Equation 14 gave:

$$\pi = \frac{1}{2}\int_0^1\int_0^1\left(\frac{\partial^4\Delta H_1}{\alpha^4\partial R^4}.\Delta H_1 + \frac{2\partial^4\Delta H_1}{\alpha^2\partial R^2\partial Q^2}.\Delta H_1 + \frac{\partial^4\Delta H_1}{\partial Q^4}.\Delta H_1\right)\partial R\partial Q - \frac{1}{D}\int_0^1\int_0^1\left[qb^4.\Delta H_1 + \frac{h}{2\alpha^2}\left(\frac{\partial^2\Delta^2 H_2}{\partial Q^2}\frac{\partial^2\Delta H_1}{\partial R^2}.\Delta H_1 + \frac{\partial^2\Delta^2 H_2}{\partial R^2}\frac{\partial^2\Delta H_1}{\partial Q^2}.\Delta H_1 - \frac{2\partial^2\Delta^2 H_2}{\partial R\partial Q}.\frac{\partial^2\Delta H_1}{\partial R\partial Q}.\Delta H_1\right)\right]\partial R\partial Q \quad \ldots 15$$

Factorizing coefficient factor Δ out reduced Equation 15 to

$$\pi = \frac{\Delta^2}{2}\int_0^1\int_0^1\left(\frac{\partial^4 H_1}{\alpha^4\partial R^4}.H_1 + \frac{2\partial^4 H_1}{\alpha^2\partial R^2\partial Q^2}.H_1 + \frac{\partial^4 H_1}{\partial Q^4}.H_1\right)\partial R\partial Q - \frac{1}{D}\int_0^1\int_0^1\left[\Delta.qb^4.H_1 + \frac{\Delta^4 h}{2\alpha^2}\left(\frac{\partial^2 H_2}{\partial Q^2}\frac{\partial^2 H_1}{\partial R^2}.H_1 + \frac{\partial^2 H_2}{\partial R^2}\frac{\partial^2 H_1}{\partial Q^2}.H_1 - \frac{2\partial^2 H_2}{\partial R\partial Q}.\frac{\partial^2 H_1}{\partial R\partial Q}.H_1\right)\right]\partial R\partial Q \quad \ldots 16$$

6. MINIMIZATION OF TOTAL POTENTIAL ENERGY

Minimization of total potential energy is a very vital aspect of variational principle in which the functional was decomposed. Equation 16 was therefore minimized by differentiating total potential energy partially with respect to deflection coefficient, thereby reducing the power of deflection coefficient from four to three. The minimized total potential energy gave:

$$\frac{\partial \pi}{\partial \Delta} = \Delta \int_0^1 \int_0^1 \left(\frac{\partial^4 H_1}{\propto^4 \partial R^4} . H_1 + \frac{2\partial^4 H_1}{\propto^2 \partial R^2 \partial Q^2} . H_1 + \frac{\partial^4 H_1}{\partial Q^4} . H_1 \right) \partial R \partial Q - \frac{1}{D} \int_0^1 \int_0^1 q b^4 . H_1 \partial R \partial Q - \frac{2\Delta^3 h}{D \propto^2} \int_0^1 \int_0^1 \left(\frac{\partial^2 H_2}{\partial Q^2} \frac{\partial^2 H_1}{\partial R^2} . H_1 + \frac{\partial^2 H_2}{\partial R^2} \frac{\partial^2 H_1}{\partial Q^2} . H_1 - \frac{2\partial^2 H_2}{\partial R \partial Q} . \frac{\partial^2 H_1}{\partial R \partial Q} . H_1 \right) \partial R \partial Q \quad \text{.......... 17}$$

7. AMPLITUDE EQUATION FOR SSSS PLATE

Amplitude equation determines the extent of plate deflection, the larger the amplitude the larger the deflection and vice versa. In determining this amplitude, reference was made to the displacement functions in Equation 12 and stress functions in 13, hence:

$$H_1 = (R^2 - 2R^3 + R^4)(Q^2 - 2Q^3 + Q^4) \quad \text{.................................. 18}$$

$$H_2 = \frac{\beta \Delta^2}{6350400} [(28R^6 - 72R^7 + 78R^8 - 40R^9 + 8R^{10})(28Q^6 - 72Q^7 + 78Q^8 - 40Q^9 + 8Q^{10}) - (14R^6 - 48R^7 + 57R^8 - 30R^9 + 6R^{10})(14Q^6 - 48Q^7 + 57Q^8 - 30Q^9 + 6Q^{10})] \quad \text{............. 19}$$

Substituting Equations 18 and 19 into Equation 17 and carrying out the respective differentiation and integration accordingly (it was done in parts).

The first term in the Equation after differentiation and integration gave:

$$\int_0^1 \int_0^1 \frac{\partial^4 H_1}{\propto^4 \partial R^4} . H_1 \, \partial R \partial Q = \frac{1.26984127e^{-3}}{\propto^4} \quad \text{........................... 20}$$

The second term in the Equation after differentiation and integration gave:

$$\int_0^1 \int_0^1 2 \frac{\partial^4 H_1}{\propto^2 \partial R^2 \partial Q^2} . H_1 \, \partial R \partial Q = \frac{7.25623583e^{-4}}{\propto^2} \quad \text{.................. 21}$$

The third term in the Equation after differentiation and integration gave:

$$\int_0^1 \int_0^1 \frac{\partial^4 H_1}{\partial Q^4} . H_1 \, \partial R \partial Q = 1.26984127e^{-3} \quad \text{..................... 22}$$

The fourth term in the Equation after differentiation and integration gave:

$$\int_0^1 \int_0^1 H_1 \, \partial R \partial Q = 1.111111111e^{-3} \quad \text{.......................... 23}$$

The fifth term in the Equation after differentiation and integration gave:

$$\int_0^1 \int_0^1 \frac{\partial^2 H_2}{\partial Q^2} \frac{\partial^2 H_1}{\partial R^2} . H_1 \, \partial R \partial Q = -3.818286009 \beta e^{-12} \quad \text{......... 24}$$

The sixth term in the Equation after differentiation and integration gave:

$$\int_0^1 \int_0^1 \frac{\partial^2 H_2}{\partial R^2} \frac{\partial^2 H_1}{\partial Q^2} . H_1 \, \partial R \partial Q = -3.818286009 \beta e^{-12} \quad \text{........ 25}$$

The seventh term in the Equation after differentiation and integration gave:

$$\int_0^1 \int_0^1 2 \frac{\partial^2 H_2}{\partial R \partial Q} \frac{\partial^2 H_1}{\partial R \partial Q} . H_1 \partial R \partial Q = 7.137525527 \beta e^{-12} \quad \text{... 26}$$

Substituting Equations 20, 21, 22, 23, 24, 25, and 26 into Equation 17 gave:

$$\left(\frac{1.26984127e^{-3}}{\propto^4} + \frac{7.25623583e^{-4}}{\propto^2} + 1.26984127e^{-3} \right) \Delta - 1.111111111e^{-3} \frac{q b^4}{D} - [(-3.818286009e^{-12}) + (-3.818286009e^{-12}) - (7.137525527e^{-12})] \frac{2\Delta^3 \beta h}{\propto^2 D} = 0 \quad \text{................ 27}$$

Recall that $\beta = \frac{E}{\propto^2 \left(\frac{1}{\propto^4} + \frac{2}{\propto^2} + 1 \right)}$ and 28

$$D = \frac{E h^3}{12(1 - \mu^2)} \quad \text{... 29}$$

Combining Equations 28 and 29 together gave:

$$\beta = \frac{12(1-\mu^2)D}{h^3\propto^2\left(\frac{1}{\propto^4}+\frac{2}{\propto^2}+1\right)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 30$$

Substituting Equation 30 into Equation 27 gave:

$$(3.545783411e^{-10})\frac{(1-\mu^2)\Delta^3}{h^2(1+2\propto^2+\propto^4)} + \left(\frac{1.26984127e^{-3}}{\propto^4} + \frac{7.25623583e^{-4}}{\propto^2} + 1.26984127e^{-3}\right)\Delta - 1.111111111e^{-3}\frac{qb^4}{D} = 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 31$$

Recall that $w = \Delta H_1 = \Delta(R^2 - 2R^3 + R^4)(Q^2 - 2Q^3 + Q^4)$ ……32

Equation 31 gives the amplitude equation for SSSS thin rectangular plate, which is in the form of a cubic equation: $K_1\Delta^3 + K_2\Delta + K_3 = 0$, where K_1, K_2, K_3 are constants. This cubic equation was solved and deflection coefficient obtained. Newton-Raphson method was used in solving for this deflection coefficient.

8. RESULTS AND DISCUSSION

Table 1: Coefficient of Deflection for CCCC Plate with $v = 0.3$

Aspect ratio $(\propto = \frac{a}{b})$	$\frac{W(0,0)}{qb^4/D}$					Difference in the results							
	P	M	I & G	E	S	D	% D	D	% D	D	% D	D	% D
1	0.0013	0.00126532	0.00126725	0.00126	0.00126541	0.000035	2.7661	0.00003275	2.5192	0.00004	3.1746	0.00004599	3.6344
1.1	0.0016	-	-	-	3. -	-	-		-	-		-	
1.2	0.0017	-	0.00172833	0.00172	0.00172495	-		0.00002833	1.6392	0.00002	1.1628	0.00002495	1.4464
1.3	0.0018	-	-	-	-	-	-	-	-	-			
1.4	0.0019	-	0.00207217	0.00207	-	-		0.0001722	8.3108	0.00017	6.2963	-	
1.5	0.0019	0.00219652	-	-	0.00219658	0.0002952	13.4303		-	-		0.00029658	13.5019

[M]: Milan (2010); [I&G]: Imark and Gerdemeli (2017); [E]: Evans (1939); [S]: Shuang (2007); [P]: Present; [D]: Difference; [%D]: Percentage Difference

Table 1 summarized the results obtained by the present and previous researchers. There are many authors who had worked on this boundary condition with different methods. These methods are to a greater extent an approximation method. Imark and Gerdemeli [5] in the comparison presented an exact solution of CCCC rectangular thin plate under uniform load, in which each term of the series is trigonometric and hyperbolic. Shuang [12] used symplectic elasticity approach for exact bending solution of rectangular thin plate.

However, all the previous researchers thus far used trigonometry as their shape function against the polynomial used in this study. Regardless of these methods used by the previous and present researchers, a correlation exist in their results. The percentage difference in their results are within the accepted limit in statistics. This implies that a reasonable agreement exist in the results of this work and those of past work.

9. Discussion on the Deflection, *w* for CCCC plate

The preceding section evaluated the deflection coefficient of CCCC plate under a unit load. In this season, the numerical studies of deflection under different loading were evaluated, which forms the baseline for understanding the dynamics of this plate under the said loads.

Geometrical nonlinear analysis of this plate was carried out by using three different load intensities.

Equations 31 and 32 were used in carrying out this geometrical nonlinear analysis of CCCC steel thin rectangular plate. The values obtained from this analysis were tabulated in Table 1 and these values of deflection were plotted against the aspect ratio as shown in the Figure 2.

In this analysis, the linear dimension, a, was kept constant while the linear dimension, b, was varied. This variations was made in such a way that the linear dimension, b, was on the decrease. The deflections of each load presented in the table were plotted against the aspect ratio of the plate, different colours were used to differentiate the loads against each other.

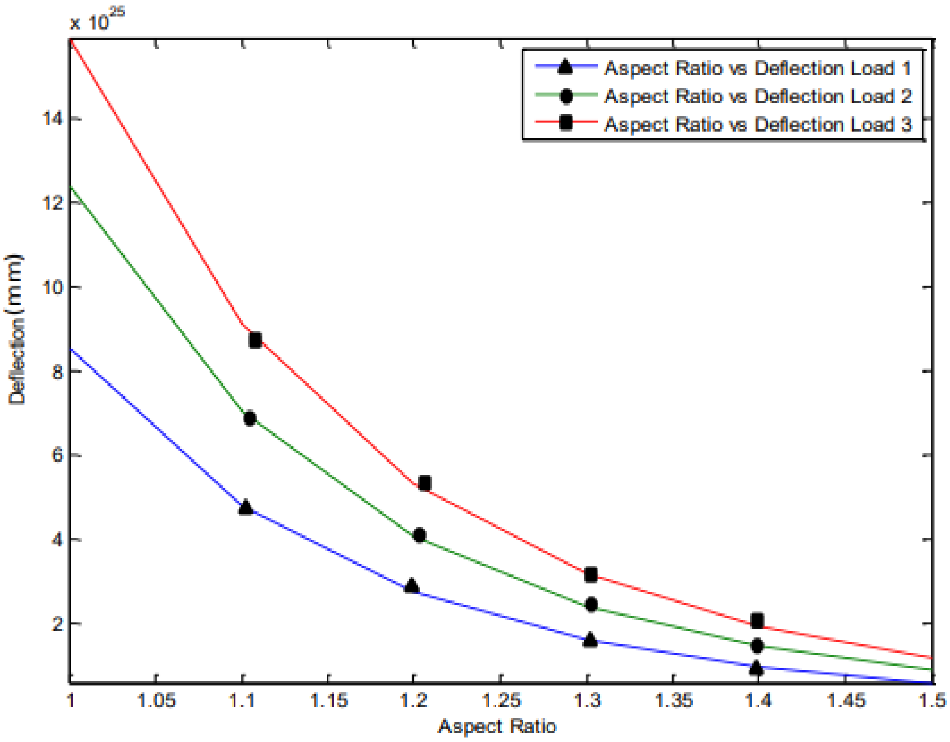

Figure 2: Relationship between the deflections Aspect Ratio of CCCC plate

The graph shows that the deflection decreases gradually as the aspect ratio increases. From the tabulated values, the deflection is higher at the aspect ratio 1.0 than the others. This implies that the deflection is quite stable when the aspect ratio is higher. One can therefore conclude that the deflection is a function of the linear dimension of the plate. From the three loads used it could also be affirmed that the deflection will continue to decrease as long as there is an increase in the aspect ratio.

10. CONCLUSION

In sincerity this thesis present a breakthrough in the analysis of large deflection of thin rectangular plate. The major problem facing the analysis of large deflection of thin plate has been on how to solve the coupled equation of Von Karman. The previous researchers assumed solutions for this equations but, this shortcoming has been overcome with the advance of this work which has successfully obtained the general expressions for deflection and stress function by direct integration of Von Karman compatibility and equilibrium equations.

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