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Effect of Michell's Function in Stress Analysis Due to Axisymmetric Heat Supply of a Limiting Plate

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ABSTRACT

The present paper deals with the determination of quasi static thermal stresses in a limiting thick circular plate subjected to arbitrary heat flux on upper and lower surface and the fixed circular edge is thermally insulated. Initially the limiting thick circular plate is at zero temperature. Here we modify Kulkarni (2009) and compute the effects of Michell function on the limiting thickness of circular plate by using stress analysis with internal heat generation and axisymmetric heat supply in terms of stresses along radial direction. The governing heat conduction equation has been solved by the method of integral transform technique. The results are obtained in a series form in terms of Bessel's functions. The results for stresses have been computed numerically and illustrated graphically.

Keywords: Quasi static thermal stresses, limiting thick plate $(M \neq 0)$, limiting thin plate $(M = 0)$, internal heat generation, axisymmetric heat supply.

I. INTRODUCTION

During the last century the theory of elasticity has found of considerable applications in the solution of engineering problems. Thermoelasticity contains the generalized theory of heat conductions, thermal stresses. A considerable progress in the field of air-craft and machine structures, mainly with gas and steam turbines and the emergence of new topics in chemical engineering have given rise to numerous problems in which thermal stresses play an important role and frequently even a primary role. Nowacki [1] has determined the temperature distribution on the upper face, with zero temperature on the lower face and the circular edge thermally insulated. Bhongade and Durge [2] studied an inverse steady state thermal stresses in a thin clamped circular plate with internal heat generation. Bhongade and Durge [3] considered thick circular plate and discuss the effect of Michell function on steady state behavior of thick circular plate, now here we consider a limiting thick circular plate subjected to arbitrary heat flux on upper and lower surface and the fixed circular edge is thermally insulated. Initially the plate is at zero temperature. Here we modify Kulkarni [4] and compute the effects of Michell function on the limiting thickness of circular plate by using stress analysis with internal heat generation and axisymmetric heat supply in terms of stresses along radial direction. The governing heat conduction equation has been solved by the method of integral transform technique. The results are obtained in a series form in terms of Bessel's functions. The results for stresses have been computed numerically and illustrated graphically. A mathematical model has been constructed with the help of numerical illustration by considering steel (0.5% carbon) limiting thick circular plate. No one previously studied such type of problem. This is new contribution to the field.

The direct problem is very important in view of its relevance to various industrial mechanics subjected to heating such as the main shaft of lathe, turbines and the role of rolling mill, base of furnace of boiler of a thermal power plant and gas power plant.

II. FORMULATION OF THE PROBLEM

Consider a limiting thick $(M \neq 0)$ circular plate of radius a and thickness $2h$ defined by $0 \leq r \leq a, -h \leq z \leq h$. Initially the plate is at zero temperature. Let the plate be subjected to axisymmetric arbitrary heat flux $\pm f(r,t)$ prescribed over the upper surface $(z = h)$ and the lower surface $(z = -h)$. The fixed circular edge $(r = a)$ is thermally insulated. Assume a limiting thick circular plate with internal heat generation is free from traction. Under these prescribed conditions, the quasi static transient thermal stresses are required to be determined.

The differential equation governing the displacement potential function $\phi(r,z,t)$ is given as

$$\frac{\partial^2 \phi}{\partial r^2} + \frac{1}{r}\frac{\partial \phi}{\partial r} + \frac{\partial^2 \phi}{\partial z^2} = K\boldsymbol{\tau} \tag{1}$$

Where K is the restraint coefficient and temperature change $\tau = T - T_{i,}\ T_i$ is initial

temperature. Displacement function ϕ is known as Goodier's thermoelastic displacement potential.
The temperature of the plate at time *t* satisfying the heat conduction equation as follows,

$$\frac{\partial^2 T}{\partial r^2}+\frac{1}{r}\frac{\partial T}{\partial r}+\frac{\partial^2 T}{\partial z^2}+\frac{q}{k}=\frac{1}{\alpha}\frac{\partial T}{\partial t} \qquad (2)$$

with the boundary conditions

$$T = \pm f(r,t)\ at\ z=\pm h,\ 0\le r\le a \qquad (3)$$

$$\frac{\partial T}{\partial r}=0\ at\ r=a, -h\le z\le h \qquad (4)$$

$$q(r,z,t)=\delta(r-r_0)\sin(\beta_m z)\,(1-e^{-t}),\ 0<r_0<a \qquad (5)$$

and the initial condition

$$T=0 \qquad \text{at}\ \ t=0 \qquad (6)$$

where α is the thermal diffusivity of the material of the plate, k is the thermal conductivity of the material of the plate, q is the internal heat generation and $\delta(r)$ is well known dirac delta function of argument *r*.
The Michell's function *M* must satisfy

$$\nabla^2\nabla^2 M=0 \qquad (7)$$

Where

$$\nabla^2=\frac{\partial^2}{\partial r^2}+\frac{1}{r}\frac{\partial}{\partial r}+\frac{\partial^2}{\partial z^2} \qquad (8)$$

The components of the stresses are represented by the thermoelastic displacement potential ϕ and Michell's function *M* as

$$\sigma_{rr}=2G\left\{\frac{\partial^2\phi}{\partial r^2}-K\tau+\frac{\partial}{\partial z}\left[\nu\nabla^2 M-\frac{\partial^2 M}{\partial r^2}\right]\right\} \qquad (9)$$

$$\sigma_{\theta\theta}=2G\left\{\frac{1}{r}\frac{\partial\phi}{\partial r}-K\tau+\frac{\partial}{\partial z}\left[\nu\nabla^2 M-\frac{1}{r}\frac{\partial M}{\partial r}\right]\right\} \qquad (10)$$

$$\sigma_{zz}=2G\left\{\frac{\partial^2\phi}{\partial z^2}-K\tau+\frac{\partial}{\partial z}\left[(2-\nu)\nabla^2 M-\right.\right.$$
∂2M∂z2

(11) and

$$\sigma_{rz}=2G\left\{\frac{\partial^2\phi}{\partial r\partial z}+\frac{\partial}{\partial r}\left[(1-\nu)\nabla^2 M-\frac{\partial^2 M}{\partial z^2}\right]\right\} \qquad (12)$$

Where *G* and *v* are the shear modulus and Poisson's ratio respectively.
For traction free surface stress functions

$$\sigma_{rr}=\sigma_{rz}=0\ at\ z=h \qquad (13)$$

Equations (1) to (13) constitute mathematical formulation of the problem.

III. SOLUTION

To obtain the expression for temperature *T* (*r*, *z*, *t*), we introduce the finite Hankel transform over the variable *r* and its inverse transform defined as

$$\bar{T}(\beta_m,z,t)=\int_0^a r\,K_0(\beta_m,r)\,T(r,z,t)\,dr \qquad (14)$$

$$T(r,z,t)=\sum_{m=1}^{\infty}K_0(\beta_m,r)\,\bar{T}(\beta_m,z,t) \qquad (15)$$

Where,

$$K_0(\beta_m,r)=\frac{\sqrt{2}}{a}\frac{J_0(\beta_m r)}{J_0(\beta_m a)}, \qquad (16)$$

$\beta_1,\beta_2\ldots\ldots$ are roots of transcendental equation

$$J_1(\beta_m a)=0 \qquad (17)$$

Where $J_n(x)$ is Bessel function of the first kind of order n.
On applying the finite Hankel transform defined in the Eq. (14), its inverse transform defined in (15) and applying Laplace transform and its inverse by residue method successively to the Eq. (2), one obtains the expression for temperature as

$$T(\mathrm{r,z,t})=\sum_{m=1}^{\infty}\sum_{n=1}^{\infty}\frac{\sqrt{2}}{a}\frac{J_0(\beta_m r)}{J_0(\beta_m a)}$$

$$\times\left(\frac{n\pi\alpha}{2(-1)^n h^2}\right)\left\{\left[\sin\left[\frac{n\pi}{2h}(z+h)\right]+\sin\left[\frac{n\pi}{2h}(z-h)\right]\right]g(t)\right\}$$

$$+\left[\frac{1}{2\alpha\beta_m{}^2}+\frac{e^{-t}}{1-2\alpha\beta_m{}^2}+\right.$$
e− 2αβm 2*t*2αβm 2(2αβm 2− 1)*αDm*sinβm*z* *k*
(18)

where

$$D_m=\frac{\sqrt{2}}{a}\frac{r_0 J_0(\beta_m r_0)}{J_0(\beta_m a)}$$

$$g(t)=\int_0^t e^{-\alpha\left[\beta_m{}^2+\frac{n^2\pi^2}{4h^2}\right](t-u)}$$

$$\times\left[\frac{\alpha\,D_m}{k}\sin(\beta_m h)\left(\frac{1}{2\alpha\beta_m{}^2}+\frac{e^{-u}}{1-2\alpha\beta_m{}^2}+\right.\right.$$
e− 2αβm 2*u*2αβm 22αβm 2− 1−*ᶠβm*,u *du*

Since initial temperature $T_i=0, \tau=T-T_i$

$$\tau=T \qquad (19)$$

Michell's function *M*

Now let's assume that Michell's function *M*, which satisfy Eq.(7) is given by

$$M = \left(\frac{\sqrt{2}}{a}K\right)\sum_{m=1}^{\infty}\sum_{n=1}^{\infty}\frac{J_0(\beta_m r)}{J_0(\beta_m a)}f(r,t) \times [B_{mn}\sinh(\beta_m z) + C_{mn}\,\beta_m z\cosh(\beta_m z)] \tag{20}$$

Where B_{mn} and C_{mn} are arbitrary functions, which can be determined by using condition (13).

Goodiers Thermoelastic Displacement Potential $\phi(r,z,t)$

Assuming the displacement function $\phi(r,z,t)$ which satisfies Eq. (1) as

$$\phi(r,z,t) = K\sum_{m=1}^{\infty}\sum_{n=1}^{\infty}\frac{\sqrt{2}}{a}\frac{J_0(\beta_m r)}{J_0(\beta_m a)}\left(\frac{-n\pi\alpha}{2(-1)^n h^2}\right)\frac{1}{\left(\beta_m^2+\frac{n^2\pi^2}{4h^2}\right)} \times \left[\sin[\tfrac{n\pi}{2h}(z+h)] + \sin[\tfrac{n\pi}{2h}(z-h)]\right]g(t) - \left(\frac{\alpha D_m}{2k\beta_m^2}\right)\left[\frac{1}{2\alpha\beta_m^2} + \frac{e^{-t}}{1-2\alpha\beta_m^2} + \frac{e^{-2\alpha\beta_m^2 t}}{2\alpha\beta_m^2(2\alpha\beta_m^2-1)}\right]\sin\beta_m z \tag{21}$$

Now using Eqs. (18), (20) and (21) in Eqs. (9), (10), (11) and (12), one obtains the expressions for stresses respectively as

$$\frac{\sigma_{rr}}{K} = 2G\sum_{m=1}^{\infty}\sum_{n=1}^{\infty}\frac{\sqrt{2}}{a}\frac{1}{J_0(\beta_m a)}\left\{\left(\frac{n\pi\alpha}{2(-1)^n h^2}\right)\left[\frac{\beta_m^2 J_1'(\beta_m r)}{\left(\beta_m^2+\frac{n^2\pi^2}{4h^2}\right)} - J_0(\beta_m r)\right] \times \left[\sin[\tfrac{n\pi}{2h}(z+h)] + \sin[\tfrac{n\pi}{2h}(z-h)]\right]g(t) + \frac{\alpha D_m\sin(\beta_m z)}{k}\left[\frac{J_1'(\beta_m r)}{2\left(\beta_m^2+\frac{n^2\pi^2}{4h^2}\right)} - J_0(\beta_m r)\right]\left[\frac{1}{2\alpha\beta_m^2}+\frac{e^{-t}}{1-2\alpha\beta_m^2}+\frac{e^{-2\alpha\beta_m^2 t}}{2\alpha\beta_m^2(2\alpha\beta_m^2-1)}\right] + J_1'(\beta_m r)\,\beta_m^2[B_{mn}\,\beta_m F(\beta_m,t)\cosh(\beta_m z)] + C_{mn}\,\beta_m^2\left[\begin{matrix}2\nu\,\beta_m J_0(\beta_m r)\cosh(\beta_m z) + F(\beta_m,t)\,J_1'(\beta_m r)\\ \times(\beta_m\cosh(\beta_m z) + \beta_m^2 z\sinh(\beta_m z))\end{matrix}\right]\right\} \tag{22}$$

$$\frac{\sigma_{\theta\theta}}{K} = 2G\sum_{m=1}^{\infty}\sum_{n=1}^{\infty}\frac{\sqrt{2}}{a}\frac{1}{J_0(\beta_m a)}\left\{\left(\frac{n\pi\alpha}{2(-1)^n h^2}\right)\left[\frac{\beta_m J_1(\beta_m r)}{r\left(\beta_m^2+\frac{n^2\pi^2}{4h^2}\right)} - J_0(\beta_m r)\right] \times \left[\sin[\tfrac{n\pi}{2h}(z+h)] + \sin[\tfrac{n\pi}{2h}(z-h)]\right]g(t) + \frac{\alpha D_m\sin(\beta_m z)}{k}\left[\frac{J_1(\beta_m r)}{2\beta_m r\left(\beta_m^2+\frac{n^2\pi^2}{4h^2}\right)} - J_0(\beta_m r)\right]\left[\frac{1}{2\alpha\beta_m^2}+\frac{e^{-t}}{1-2\alpha\beta_m^2}+\frac{e^{-2\alpha\beta_m^2 t}}{2\alpha\beta_m^2(2\alpha\beta_m^2-1)}\right] + B_{mn}\,\beta_m^2 F(\beta_m,t)\cosh(\beta_m z)\frac{J_1(\beta_m r)}{r} + C_{mn}\,\beta_m^2 F(\beta_m,t)\left[\begin{matrix}2\nu\,\beta_m J_0(\beta_m r)\cosh(\beta_m z) + \cosh(\beta_m z)\frac{J_1(\beta_m r)}{r}\\ \times\beta_m z\sinh(\beta_m z)\end{matrix}\right]\right\} \tag{23}$$

$$\frac{\sigma_{zz}}{K} = 2G\sum_{m=1}^{\infty}\sum_{n=1}^{\infty}\frac{\sqrt{2}}{a}\frac{J_0(\beta_m r)}{J_0(\beta_m a)}\left\{\left(\frac{n^3\pi^3\alpha}{8(-1)^n h^4}\right)\frac{1}{\left(\beta_m^2+\frac{n^2\pi^2}{4h^2}\right)} \times \left[\left[\sin[\tfrac{n\pi}{2h}(z+h)] + \sin[\tfrac{n\pi}{2h}(z-h)]\right]g(t) + \frac{\alpha D_m\sin(\beta_m z)}{2k}\left[\frac{1}{2\alpha\beta_m^2}+\frac{e^{-t}}{1-2\alpha\beta_m^2}+\frac{e^{-2\alpha\beta_m^2 t}}{2\alpha\beta_m^2(2\alpha\beta_m^2-1)}\right]\right] - \left(\frac{n\pi\alpha}{2(-1)^n h^2}\right)\left[\sin[\tfrac{n\pi}{2h}(z+h)] + \sin[\tfrac{n\pi}{2h}(z-h)]\right]g(t) - B_{mn}\,\beta_m^2 F(\beta_m,t)\sinh(\beta_m z) + C_{mn}\,\beta_m^2 F(\beta_m,t) \times [2(1-\nu)\sinh(\beta_m z) - \beta_m z\cosh(\beta_m z)]\right\} \tag{24}$$

$$\frac{\sigma_{rz}}{K} = 2G\sum_{m=1}^{\infty}\sum_{n=1}^{\infty}\frac{\sqrt{2}}{a}\frac{\beta_m J_1(\beta_m r)}{J_0(\beta_m a)}\left(\frac{n^2\pi^2\alpha}{4(-1)^n h^3}\right)\frac{1}{\left(\beta_m^2+\frac{n^2\pi^2}{4h^2}\right)} \times \left(\cos[\tfrac{n\pi}{2h}(z+h)] + \cos[\tfrac{n\pi}{2h}(z-h)]\right)g(t) + \frac{\alpha D_m\cos(\beta_m z)}{2k\beta_m}\left[\frac{1}{2\alpha\beta_m^2}+\frac{e^{-t}}{1-2\alpha\beta_m^2}+\frac{e^{-2\alpha\beta_m^2 t}}{2\alpha\beta_m^2(2\alpha\beta_m^2-1)}\right] - B_{mn}\,\beta_m^2 F(\beta_m,t)\sinh(\beta_m z) + C_{mn}\,\beta_m^2 F(\beta_m,t) \times [2\nu\sinh(\beta_m z) - \beta_m z\cosh(\beta_m z)] \tag{25}$$

In order to satisfy condition Eq. (13), solving Eqs. (22) and (25) for B_{mn} and C_{mn} one obtains

$$C_{mn} = \{$$

$$\frac{1}{\beta_m{}^2 R}\left[-\frac{\alpha\, D_m}{k}\sin(\beta_m h)\sinh(\beta_m h)\right]\left[\frac{J_1{}'(\beta_m a)}{2\left(\beta_m{}^2+\frac{n^2\pi^2}{4h^2}\right)}-J_0(\beta_m a)\right]$$

$$\times\left(\frac{1}{2\alpha\beta_m{}^2}+\frac{e^{-t}}{1-2\alpha\beta_m{}^2}+\frac{e^{-2\alpha\beta_m{}^2 t}}{2\alpha\beta_m{}^2(2\alpha\beta_m{}^2-1)}\right)+J_1{}'(\beta_m a)\,\beta_m\cosh(\beta_m h)$$

$$\times\left[\left(\frac{-n^2\pi^2\alpha}{4(-1)^n h^3}\right)\frac{g(t)\,\langle(-1)^n+1\rangle}{\left(\beta_m{}^2+\frac{n^2\pi^2}{4h^2}\right)}-\right.$$

α $Dm2k\beta m$
cosβmh $12\alpha\beta m2+e-t1-2\alpha\beta m2+e-2\alpha\beta m2t2\alpha\beta m2(2\alpha\beta m2-1)$ (26)

$$B_{mn} = \frac{-1}{\beta_m{}^2 R}\left\{\frac{\alpha\, D_m}{k}\sin(\beta_m h)\left[\frac{\beta_m{}^2 J_1{}'(\beta_m a)}{2\left(\beta_m{}^2+\frac{n^2\pi^2}{4h^2}\right)}-J_0(\beta_m a)\right]\left(\frac{1}{2\alpha\beta_m{}^2}+\frac{e^{-t}}{1-2\alpha\beta_m{}^2}+\frac{e^{-2\alpha\beta_m{}^2 t}}{2\alpha\beta_m{}^2(2\alpha\beta_m{}^2-1)}\right)\right.$$

$$\times\left[2v\sinh(\beta_m h)-\beta_m h\cosh(\beta_m h)\right]$$

$$+\frac{1}{F(\beta_m,t)}\begin{bmatrix}2v\,\beta_m J_0(\beta_m a)\cosh(\beta_m h)+J_1{}'(\beta_m a)\,F(\beta_m,t)\\ \times\,(\beta_m\cosh(\beta_m h)+\beta_m{}^2 h\sinh(\beta_m h))\end{bmatrix}$$

$$\times\left[\left(\frac{-n^2\pi^2\alpha}{4(-1)^n h^3}\right)\frac{g(t)\,\langle(-1)^n+1\rangle}{\left(\beta_m{}^2+\frac{n^2\pi^2}{4h^2}\right)}-\frac{\alpha\, D_m}{2k\beta_m}\cos(\beta_m h)\left(\frac{1}{2\alpha\beta_m{}^2}+\frac{e^{-t}}{1-2\alpha\beta_m{}^2}+\frac{e^{-2\alpha\beta_m{}^2 t}}{2\alpha\beta_m{}^2(2\alpha\beta_m{}^2-1)}\right)\right] \quad (27)$$

where

$$R = J_1{}'(\beta_m a)\,\beta_m\,F(\beta_m,t)\sinh(\beta_m h)\,\left[2v\sinh(\beta_m h)-\beta_m h\cosh(\beta_m h)\right.$$

$$+\sinh(\beta_m h)\begin{bmatrix}2v\,\beta_m J_0(\beta_m a)\cosh(\beta_m h)+J_1{}'(\beta_m a)\,F(\beta_m,t)\\ \times\,(\beta_m\cosh(\beta_m h)+\beta_m{}^2 h\sinh(\beta_m h))\end{bmatrix}$$

IV. SPECIAL CASE AND NUMERICAL CALCULATIONS

Setting

$$f(r,t) = \delta(r-r_0)(1-e^{-t})$$

Where $\delta(r)$ is well known diract delta function of argument r.

$a = 2m$, for limiting thick plate $h = 0.2000000000000000000001m$ and for limiting thin plate $h = 0.1999999999999999999999\ m$, $r_0 = 1m, t = 2\ sec.$

Material Properties

The numerical calculation has been carried out for steel (0.5% carbon) thin circular plate with the material properties defined as

Thermal diffusivity $\alpha = 14.74\times 10^{-6}\ m^2 s^{-1}$,

Specific heat $c_\rho = 465$ J/kg,

Thermal conductivity $k = 53.6$ W/m K,

Poisson ratio $\vartheta = 0.35$,

Young's modulus $E = 130\ G$ pa,

Lame constant $\mu = 26.67$,

Coefficient of linear thermal expansion $a_t = 13\times 10^{-6}\ ^1/_K$

Roots of Transcendental Equation

The $\beta_1 = 1.9159$, $\beta_2 = 3.5078$, $\beta_3 = 5.0867$, $\beta_4 = 6.6618$, $\beta_5 = 8.2353$, $\beta_6 = 9.8079$ are the roots of transcendental equation $J_1(\beta_m a) = 0$. The numerical calculation and the graph has been carried out with the help of mathematical software Mat lab.

V. DISCUSSION

In this paper a limiting thick $(M \neq 0)$ and limiting thin $(M = 0)$ circular plate is considered and determined the expressions for temperature, displacement and stresses due to internal heat generation within it and we compute the effects of Michell function on the thickness of circular plate with internal heat generation in terms of stresses along radial direction by substituting $M = 0$ in Eqs. (22), (23), (24), (25), (26) and (27) and we compare the results for $M = 0, M \neq 0$ and depicted graphically. As a special case mathematical model is constructed by considering steel (0.5% carbon) circular plate with the material properties specified above.

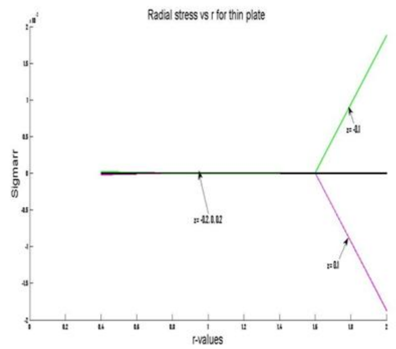

Fig.1 Radial stresses $\frac{\sigma_{rr}}{K}$ for (M= 0).

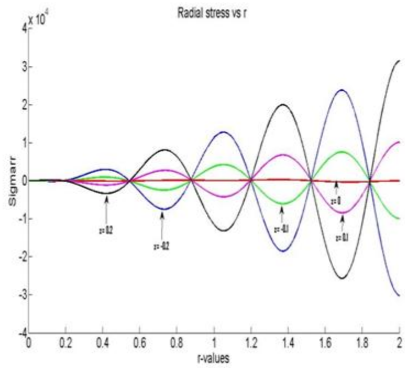

Fig. 2 Radial stresses $\frac{\sigma_{rr}}{K}$ for (M≠0).

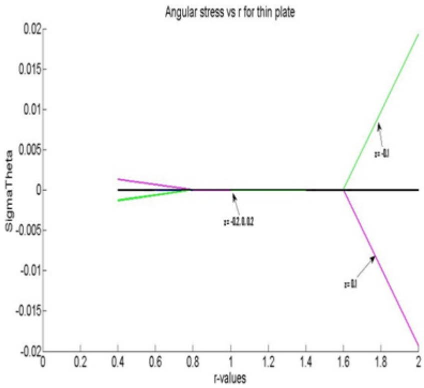

Fig. 3 Angular stresses $\frac{\sigma_{\theta\theta}}{K}$ for (M= 0).

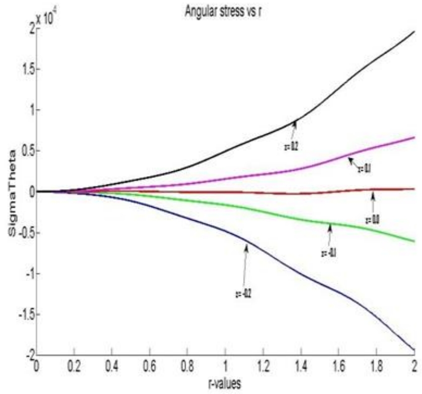

Fig. 4 Angular stresses $\frac{\sigma_{\theta\theta}}{K}$ for (M≠0).

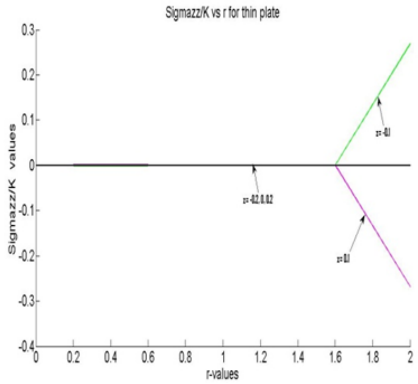

Fig. 5 Axial stresses $\frac{\sigma_{zz}}{K}$ for (M = 0).

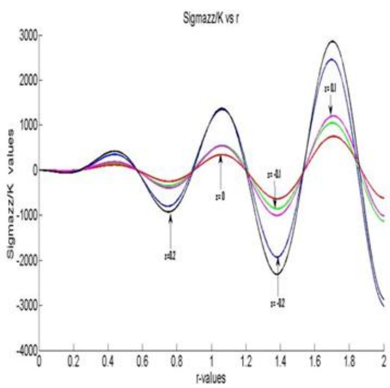

Fig. 6 Axial stresses $\frac{\sigma_{zz}}{K}$ for (M ≠0).

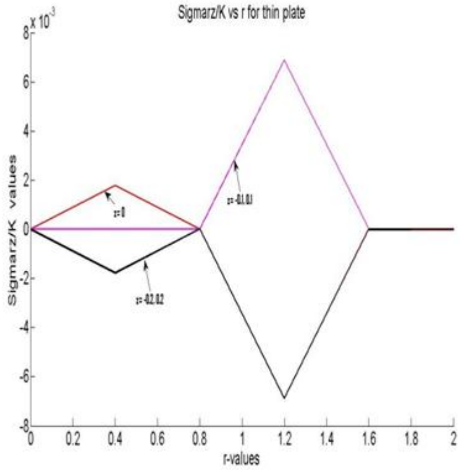

Fig. 7 Stress $\frac{\sigma_{rz}}{K}$ for (M= 0).

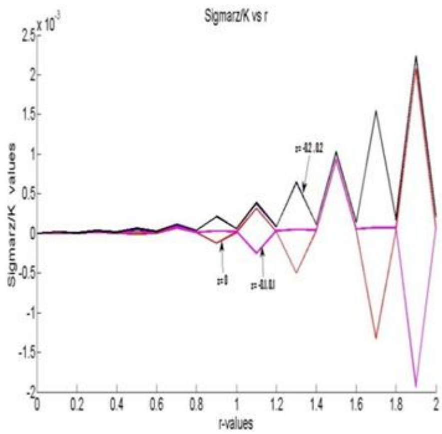

Fig. 8 Stress $\frac{\sigma_{rz}}{K}$ for (M≠ 0).

From figure 1 and 2, it is observed that due to Michell function the radial stress $\frac{\sigma_{rr}}{K}$ is increased in the range of 10^7 along radial direction. From figure 3 and 4, it is observed that due to Michell function the angular stress $\frac{\sigma_{\theta\theta}}{K}$ is increased in the range of 10^6 along radial direction.

From figure 5 and 6, it is observed that due to Michell function the axial stress $\frac{\sigma_{zz}}{K}$ is increased in the range of 10^4 along radial direction. From figure 7 and 8, it is observed that due to Michell function the stress $\frac{\sigma_{rz}}{K}$ is slightly decreased along radial direction.

VI. CONCLUSION

We can conclude that difference in the thickness of thin and thick circular plate is mechanically zero even though the radial stress $\frac{\sigma_{rr}}{K}$, angular stress $\frac{\sigma_{\theta\theta}}{K}$, axial stress $\frac{\sigma_{zz}}{K}$ are tremendously increased due to the existance of Michell function whereas stress $\frac{\sigma_{rz}}{K}$ is negligibly vary with the thickness along radial direction. The results obtained here are useful in engineering problems particularly in the determination of state of stress in circular plate and base of furnace of boiler of a thermal power plant and gas power plant.

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