

DENSITY PARAMETER IN A TRANSVERSELY AND ISOTROPIC DISC MATERIAL WITH RIGID INCLUSION

PARAMETAR GUSTINE KOD TRANSVERZALNOG IZOTROPNOG MATERIJALA DISKA SA KRUTIM UKLJUČKOM

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Keywords

- stress
- disc
- density
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- speed

Abstract

Creep deformation in a rotating annular disc made of transversely and isotropic material mounted on a shaft is studied. The analysis of stresses and strain rates within the disc of variable density and constant thickness is based on the transition theory. It has been analysed that the value of radial stress has a maximum at the inner surface for isotropic material (i.e. brass) in comparison to disc made of two transversely isotropic materials (i.e. magnesium and beryl). The method of stress and strain rates developed is illustrated with some numerical examples. The novelty in the current research is to include control factors as rotating speed and the density parameter in the consideration of the disc.

INTRODUCTION

In the circular rotating disc, creep analysis is important for understanding the behaviour and optimum design of structures. Rotating discs are considered to be one of the major subjects in the field of solid mechanics. There are many applications of rotating discs such as in flywheel, turbines, rotors, and computer disk drives. Wahl /1/ analysed creep deformation in rotating discs based on the Tresca criterion and its associated flow rule. Arya et al. /7/ discussed the problem of creep stresses in a rotating orthotropic disc. Kirkner /8/ investigated the problem of disc vibration on transversely isotropic elastic half-space. Arnold /9/ discussed the applications of thermo-elastic transversely isotropic thick-walled cylinder and disc. Shi-Ming et al. /10/ have analysed the stress in transversely isotropic half-space with load acting on surface. Christos et al. /12/ investigated the deformation of transversely isotropic discs under diametral compression. Thakur et al. /13/ solved the problem

Ključne reči

- napon
- disk
- gustina
- uključak
- brzina

Izvod

Proučena je deformacija puzanjem kod rotirajućeg prstenastog diska od transversalnog izotropnog materijala, koji je vezan za osovinu. Analiza napona i brzine deformacije diska promenljive gustine i konstantne debljine se zasniva na prelaznoj teoriji napona. Analizirano je da veličina radijalnog napona dostiže maksimum na unutrašnjoj površini izotropnog materijala (na pr. mesing), u poređenju sa diskom od dva transversalna izotropna materijala (na pr. magnezijum i berilijum). Ilustrovana je razvijena metoda napona i brzine deformacija, sa nekoliko numeričkih primera. Novina u ovom istraživanju jeste uvrštavanje kontrolnih faktora kao što su brzina rotacije i parametar gustine u razmatranje ponašanja diska.

of creep stress and strain rates for transverse material disc connected to shaft by using transition theory.

Weighted integral measures representations: the ordinary uniaxial Cauchy's measure is given by $\int_{l_0}^l \frac{dl}{l_0} = \frac{l-l_0}{l_0}$; where

l and l_0 are deformed and undeformed lengths. The first weighted measure called Hencky measure can be written as $\int_{l_0}^l \left(\frac{l_0}{l}\right) \frac{dl}{l_0} = \ln \frac{l}{l_0}$ and is widely used in plasticity problems.

But for creep problems, it is found useful only at secondary or stationary creep and not in the transient or fracture stage. The second weighted measure used by /2/ is

$\int_{l_0}^l \left(\frac{l_0}{l}\right)^2 \frac{dl}{l_0} = \frac{l-l_0}{l_0}$. In finite elasticity, Almansi and Green

measures, the deformed and undeformed states are taken as

reference frameworks respectively and are extensively used. The third weighted measures are

$$\int_{l_0}^l \left(\frac{l_0}{l}\right)^3 \frac{dl}{l_0} = \frac{1}{2} \left[1 - \left(\frac{l_0}{l}\right)^2 \right], \quad \int_{l_0}^l \left(\frac{l}{l_0}\right)^3 \frac{dl_0}{l} = \frac{1}{2} \left[\left(\frac{l}{l_0}\right)^2 - 1 \right] \text{ and}$$

in this case, the weighting functions are $(l_0/l)^3$ and $(l/l_0)^3$, respectively. An obvious generalization of these measures is

$$\int_{l_0}^l \left(\frac{l_0}{l}\right)^{n+1} \frac{dl}{l_0} = \frac{1}{n} \left[1 - \left(\frac{l_0}{l}\right)^n \right] \text{ in which the weighting function is } (l_0/l)^{n+1}. \text{ Putting } n = -2, -1, 0, 1, 2, \text{ it gives Green, Cauchy, Hencky, Swainger and Almansi measures, respectively. Thus, in the general case, if the principal Almansi and Green measures are denoted by } \varepsilon_{ii}^A \text{ and } \varepsilon_{ii}^G, \text{ the generalized measures in Cartesian coordinates may be written in the form:}$$

$$\varepsilon_{ii}^M = \int_0^{\varepsilon_{ii}^A} \left[1 - 2\varepsilon_{ii}^A \right]^{n-1} d\varepsilon_{ii}^A = \frac{1}{n} \left[1 - (1 - 2\varepsilon_{ii}^A)^{n/2} \right], \quad (i = 1, 2, 3) \quad (1)$$

$$\text{and } \varepsilon_{ii}^M = \int_0^{\varepsilon_{ii}^G} \left[1 + 2\varepsilon_{ii}^G \right]^{n-1} d\varepsilon_{ii}^G = \frac{1}{n} \left[(1 + 2\varepsilon_{ii}^G)^{n/2} - 1 \right].$$

The main objective of the present paper is to develop a consistent analytical model capable to resolve a class of control problems for the rotating disc. Due to the importance of the control problems in practical engineering designs, the burst speed of the rotating disc is investigated. We assume the density of the rotating disc along the radii ratio is:

$$\rho(r) = \rho_0 (r/r_0)^{-m}, \quad (2)$$

where: ρ_0 is the constant density at $r = b$; and m is the density variation parameter.

MATHEMATICAL MODEL AND GOVERNING EQUATIONS

Consider a thin disc made of transversely isotropic material having variable density ρ , outer radius b , inner radius a ; thickness is assumed to small, so that it is effectively in plane stress (i.e. $\tau_{zz} = 0$) and mounted on a shaft and rotating with angular speed ω as shown in Fig. 1. We assume the displacement components in cylindrical polar coordinates as /4/: $u = r(1 - \eta)$; $v = 0$; $w = dz$, where η is position function of $r = \sqrt{(x^2 + y^2)}$ and d is a constant which is the allowance for uniform longitudinal extension d . For finite deformation, the generalized components of strain are given as /4, 5/:

$$\varepsilon_{rr}^A = \frac{\partial u}{\partial r} - \frac{1}{2} \left[\left(\frac{\partial u}{\partial r}\right)^2 + \left(\frac{\partial v}{\partial r}\right)^2 + \left(\frac{\partial w}{\partial r}\right)^2 - v^2 \right] = \frac{1}{2} \left[1 - (r\eta' + \eta)^2 \right],$$

$$\varepsilon_{\theta\theta}^A = \frac{1}{r} \frac{\partial v}{\partial \theta} + \frac{u}{r} - \frac{1}{2r^2} \left[\left(\frac{\partial u}{\partial \theta}\right)^2 + r^2 \left(\frac{\partial v}{\partial \theta}\right)^2 + \left(\frac{\partial w}{\partial \theta}\right)^2 - vr^2 \frac{\partial u}{\partial \theta} + ur^2 \frac{\partial v}{\partial \theta} - v \frac{\partial u}{\partial \theta} + ur^2 \frac{\partial v}{\partial \theta} + u^2 + r^2 v^2 \right] = \frac{1}{2} [1 - \eta^2],$$

$$\varepsilon_{zz}^A = \frac{\partial w}{\partial z} - \frac{1}{2} \left[\left(\frac{\partial w}{\partial z}\right)^2 + r \left(\frac{\partial v}{\partial z}\right)^2 + \left(\frac{\partial w}{\partial z}\right)^2 \right] = \frac{1}{2} [1 - (1-d)^2],$$

$$\varepsilon_{r\theta}^A = \varepsilon_{\theta z}^A = \varepsilon_{zr}^A = 0, \quad (3)$$

where: $\eta' = d\eta/dr$.

Substituting Eq.(3) into Eq.(1), we get

$$\varepsilon_{rr} = \frac{1}{n} [1 - (r\eta' + \eta)^n], \quad \varepsilon_{\theta\theta} = \frac{1}{n} [1 - \eta^n],$$

$$\varepsilon_{zz} = \frac{1}{n} [1 - (1-d)^n], \quad \varepsilon_{r\theta} = \varepsilon_{\theta z} = \varepsilon_{zr} = 0. \quad (4)$$

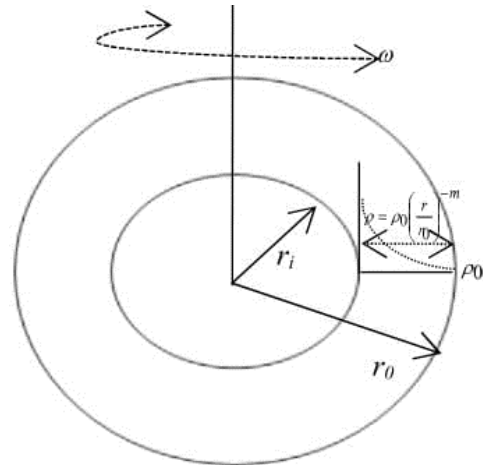


Figure 1. Geometry of isotropic rotating disc.

The stress-strain relations for magnesium and beryl (transversely isotropic material) are given by /3/ as:

$$\tau_{rr} = c_{11}\varepsilon_{rr} + c_{12}\varepsilon_{\theta\theta} + c_{13}\varepsilon_{zz},$$

$$\tau_{\theta\theta} = c_{21}\varepsilon_{rr} + c_{22}\varepsilon_{\theta\theta} + c_{23}\varepsilon_{zz},$$

$$\tau_{\theta z} = \tau_{zz} = \tau_{zr} = \tau_{rz} = 0, \quad (5)$$

where: $c_{12} = c_{11} - 2c_{66} = c_{21}$, $c_{13} = c_{31} = c_{32} = c_{23}$, $c_{55} = c_{44}$ and $c_{11} = c_{22}$, c_{33} . Substituting Eq.(5) into Eq.(4) for $n = 2$, we get strain components in terms of stresses as:

$$\varepsilon_{rr} = \frac{1}{E} [\tau_{rr} - \zeta \tau_{\theta\theta}], \quad \varepsilon_{\theta\theta} = \frac{1}{E} [\tau_{\theta\theta} - \zeta \tau_{rr}],$$

$$\varepsilon_{zz} = -\frac{\zeta}{E} [\tau_{rr} - \tau_{\theta\theta}], \quad \varepsilon_{r\theta} = \varepsilon_{\theta z} = \varepsilon_{zr} = 0, \quad (6)$$

where: $\zeta = (c_{11}c_{33} - c_{13}^2 - c_{66}c_{33}/(c_{11}c_{33} - c_{13}^2))$ and $E = 4c_{66}\zeta$ is Young's modulus.

From Eqs.(5) and (6), we get:

$$\tau_{rr} = \frac{\zeta_1}{n} [2 - \eta^n \{1 + (1+T)^n\}] - \frac{2c_{66}(1 - \eta^n)}{n},$$

$$\tau_{\theta\theta} = \frac{\zeta_1}{n} [2 - \eta^n \{1 + (1+T)^n\}] - \frac{2c_{66}}{n} [1 - \eta^n (1+T)],$$

$$\tau_{r\theta} = \tau_{\theta z} = \tau_{zr} = \tau_{zz} = 0, \quad (7)$$

where: $T = r\eta'/\eta$ is the transition function, and $\zeta_1 = c_{11} - (c_{13}^2/c_{33})$.

The equation of equilibrium is all satisfied except:

$$\frac{d}{dr} (r\tau_{rr}) = \tau_{\theta\theta} - \rho(r)\omega^2 r^2, \quad (8)$$

where: τ_{rr} , $\tau_{\theta\theta}$, $\rho(r)$ are radial, circumferential stresses and density.

Substituting Eq.(7) into Eq.(8), we obtain a nonlinear differential equation in η as:

$$\eta^{n+1}(1+T)^{n-1} \frac{dT}{d\eta} = \left[\eta^n \left\{ \frac{2c_{66}}{n\zeta_1} \left[1+nT - (1+T)^n - T\{1+(1+T)^n\} \right] + \frac{\rho\omega^2 r^2}{\zeta_1} \right\} \right], \quad (9)$$

where: $r\eta' = \eta T$. The transition points of η in Eq.(9) are $T \rightarrow -1$ and $T \rightarrow \pm\infty$. The boundary conditions are:

$$r=a, u=0 \text{ and } r=b, \tau_{rr}=0, \quad (10)$$

where: τ_{rr} and u are the radial stress and displacement component.

PROBLEM SOLUTION

To find the stresses and strain rates for creep deformation, the transition function taken (see /4, 5, 13/) at the point $T \rightarrow -1$, we define the transition functions F as:

$$F = \tau_{rr} - \tau_{\theta\theta} = \frac{2\eta^n c_{66}}{n} [1 - (1+T)^n]. \quad (11)$$

By taking logarithmic differentiation from Eq.(11), and substituting the value of $dT/d\eta$ from Eq.(9), we get:

$$\frac{d \ln F}{dr} = -\frac{1}{r} \left[\zeta_2(n-1) - 2n - \frac{n\rho\omega^2 r^2}{\zeta_1 \eta^n} \right], \quad (12)$$

where: $\zeta_2 = 2c_{66}/\zeta_1$.

The asymptotic solution of Eq.(12) as $T \rightarrow -1$ is D/r , where D being a constant. Using Eq.(2) in Eq.(12) and integrating, we get:

$$F = \tau_{rr} - \tau_{\theta\theta} = \zeta_3 r^\eta \exp(\xi), \quad (13)$$

where: ζ_3 is an integration constant, and $\xi = -n\rho_0\omega^2 r^{n-m+2}/(n+2)b^{-m}\zeta_1 D^n$, $\eta = -2n + (n-1)\zeta_2$.

Substituting Eq.(13) into Eq.(8), we get:

$$\tau_{rr} = \zeta_4 - \zeta_3 \int_r^b r^{\eta-1} \exp(\xi) dr - \frac{\rho_0\omega^2 r^{2-m}}{(2-m)b^{-m}}, \quad (14)$$

where: ζ_4 is an integration constant. Using the boundary condition Eq.(10) in Eq.(14), we get

$$\zeta_4 = \zeta_3 \int_{r=b}^b r^{\eta-1} \exp(\xi) dr - \frac{\rho_0\omega^2 b^2}{2-m}. \quad (15)$$

Substituting Eq.(15) in Eq.(14) and using Eq.(13), we get:

$$\tau_{rr} = \zeta_3 \int_r^b r^{\eta-1} \exp(\xi) dr + \frac{\rho_0\omega^2 (b^{2-m} - r^{2-m})}{(2-m)b^{-m}}, \quad (16)$$

$$\tau_{\theta\theta} = \zeta_3 \left[\int_r^b r^{\eta-1} \exp(\xi) dr - r^\eta \exp(\xi) \right] + \frac{\rho_0\omega^2 (b^{2-m} - r^{2-m})}{(2-m)b^{-m}}. \quad (17)$$

From Eq.(11), taking the asymptotic value of $T \rightarrow -1$, we get

$$\eta = \left[\frac{n\zeta_3 r^\eta \exp(\xi)}{2c_{66}} \right]^{1/n}. \quad (18)$$

The component of displacement $u = r(1 - \eta)$ from Eq.(18) becomes:

$$u = r - r \left[\frac{n\zeta_3 r^\eta \exp(\xi)}{2c_{66}} \right]^{1/n}. \quad (19)$$

Using boundary condition Eq.(10) in Eq.(19), we get:

$$\zeta_3 = \frac{2c_{66}}{na^{\eta-1} \exp(\xi_1)}, \text{ where } \xi_1 = -\frac{n\rho_0\omega^2 a^{n-m+2}}{(n-m+2)D^n \zeta_1}.$$

Substituting values of constant ζ_3 in Eqs.(16), (17) and (19), we get:

$$\tau_{rr} = \zeta_5 \int_r^b r^{\eta-1} \exp(\xi) dr + \frac{\rho_0\omega^2 (b^{2-m} - r^{2-m})}{(2-m)b^{-m}},$$

$$\tau_{\theta\theta} = \zeta_5 \left[\int_r^b r^{\eta-1} \exp(\xi) dr - r^\eta \exp(\xi) \right] - \frac{\rho_0\omega^2 (b^{2-m} - r^{2-m})}{(2-m)b^{-m}},$$

$$u = r - r \left[\frac{r^\eta \exp(\xi)}{a^\eta \exp(\xi)} \right]^{1/n}, \quad (20)$$

where: $\zeta_5 = 2c_{66}/na^n \exp(\xi_1)$.

We assume the non-dimensional components: $R = r/b$, $R_0 = a/b$, $\Omega^2 = \rho_0\omega^2 b^2/c_{66}$, $\sigma_r = \tau_{rr}/c_{66}$, $\sigma_\theta = \tau_{\theta\theta}/c_{66}$ and $U = u/b$. Stresses and displacement from Eq.(20) in non-dimensional form become:

$$\sigma_r = \left[\frac{2}{nR_0^\eta \exp(\xi_3)} \right] \int_R^1 R^{\eta-1} \exp(\xi_2) dR + \frac{\Omega^2(1-R^{2-m})}{(2-m)},$$

$$U' = R - R \left[\frac{R^\eta \exp(\xi_2)}{R_0^\eta \exp(\xi_3)} \right]^{1/n}, \quad (21)$$

$$\sigma_\theta = \left[\frac{2}{nR_0^\eta \exp(\xi_3)} \right] \left[\int_R^1 R^{\eta-1} \exp(\xi_2) dR - R^\eta \exp(\xi_2) \right] + \frac{\Omega^2(1-R^{2-m})}{(2-m)}$$

where:

$$\xi_2 = -\frac{n\Omega^2 R^{n-m+2} b^n}{2D^n (n-m+2)} \text{ and } \xi_3 = -\frac{n\Omega^2 R^{n-m+2} a^n}{2D^n (n-m+2)} \zeta_2.$$

The material constants reduce only to two constants for the isotropic case, say $c_{11} = c_{22} = c_{33}$, $c_{12} = c_{21} = c_{13} = c_{31} = c_{23} = c_{32} = c_{11} - 2c_{66}$ and $\alpha_1 = \alpha_2 = \alpha_3 = \alpha$. The constants λ and μ can be written as: $c_{12} = \lambda$, $c_{11} = \lambda + 2\mu$, $c_{66} = (c_{11} - c_{12})/2$, $c = 2\mu/(\lambda + 2\mu)$ and $1 - \zeta_2 = 1/c - c$. For the isotropic case Eq.(21) becomes:

$$\sigma_r = \left[\frac{2}{nR_0^\eta \exp(\xi_5)} \right] \int_R^1 R^{\eta-1} \exp(\xi_4) dR + \frac{\Omega^2(1-R^{2-m})}{(2-m)},$$

$$U' = R - R \left[\frac{R^\eta \exp(\xi_4)}{R_0^\eta \exp(\xi_5)} \right]^{1/n}, \quad (22)$$

$$\sigma_\theta = \left[\frac{2}{nR_0^\eta \exp(\xi_5)} \right] \left[\int_R^1 R^{\eta-1} \exp(\xi_4) dR - R^\eta \exp(\xi_4) \right] + \frac{\Omega^2(1-R^{2-m})}{(2-m)}$$

where: $\xi_4 = -\frac{n\Omega^2 R^{n-m+2} b^n}{2(2-c)D^n (n-m+2)}$, and

$$\xi_5 = -\frac{n\Omega^2 R^{n-m+2} a^n}{2(2-c)c_{33}D^n(n-m+2)} \zeta_2, \text{ and } \eta_1 = -2n + \frac{(n-1)}{(2-c)}.$$

These results are the same given Thakur et al. /13/, for the transversely and isotropic material case when $m = 0$.

ESTIMATION OF CREEP PARAMETER

The strain rates are given as Odqvist /6/:

$$\begin{aligned} \dot{\epsilon}_{rr} &= \left[\frac{n}{2}(\sigma_{rr} - \sigma_{\theta\theta}) \right]^{n-1} \left[\frac{\sigma_{rr}\zeta_8 - \sigma_{\theta\theta}\zeta_7}{4\zeta_9} \right], \\ \dot{\epsilon}_{\theta\theta} &= \left[\frac{n}{2}(\sigma_{rr} - \sigma_{\theta\theta}) \right]^{n-1} \left[\frac{\sigma_{\theta\theta}\zeta_8 - \sigma_{rr}\zeta_7}{4\zeta_9} \right], \\ \dot{\epsilon}_{zz} &= -\left[\frac{n}{2}(\sigma_{rr} - \sigma_{\theta\theta}) \right]^{n-1} \zeta_8 \left[\frac{\sigma_{rr} + \sigma_{\theta\theta}}{4\zeta_9} \right], \end{aligned} \quad (23)$$

where: $\zeta_7 = 1 - \frac{c_{13}^2}{c_{11}c_{33}}$, $\zeta_8 = \zeta_7 - 2\frac{c_{66}}{c_{11}}$, and $\zeta_9 = \frac{c_{66}}{c_{11}} - 1 + \frac{c_{13}^2}{c_{11}c_{33}}$ for $n = 1/N$, where N is the measure.

NUMERICAL RESULTS AND DISCUSSION

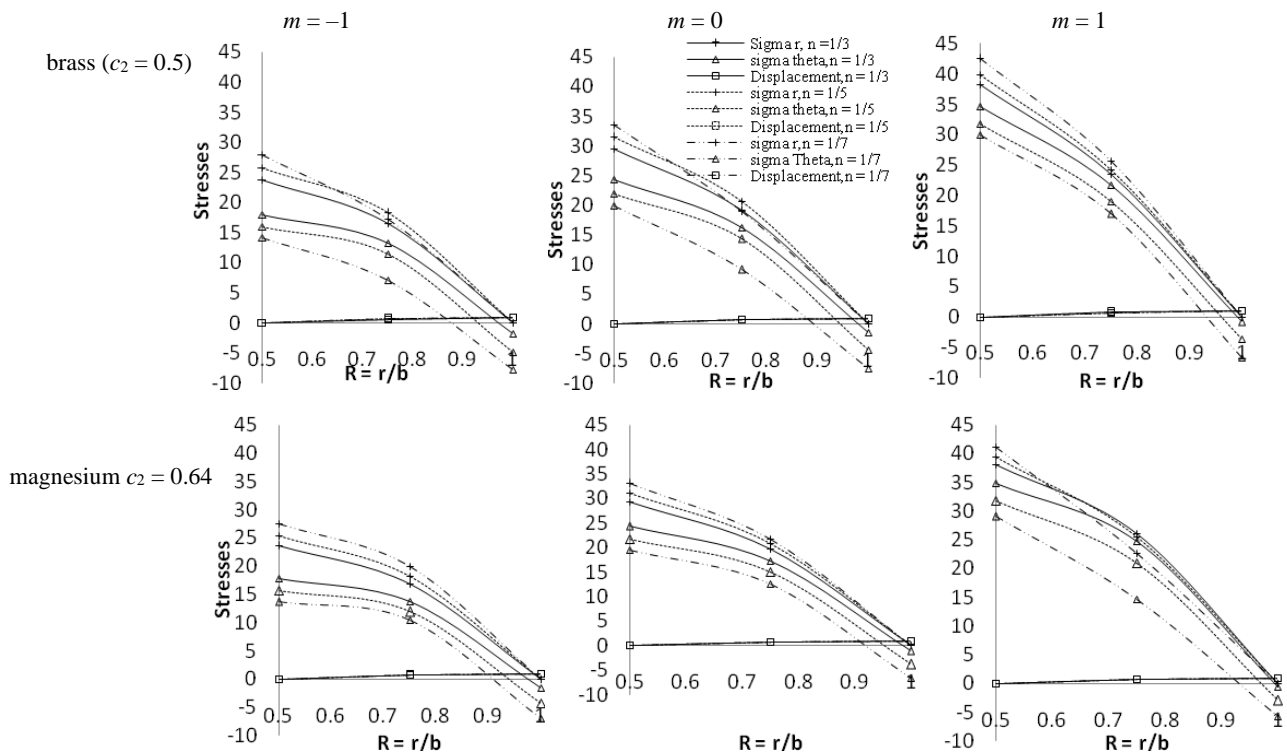
For calculating strain rates and stresses based on the above problem, the following values have been taken: transversely materials - beryl: $c_2 = 0.7, c_{11} = 2.7, c_{12} = 0.9, c_{13} = 0.7, c_{33} = 4.7, c_{44} = 0.9$; magnesium: $c_2 = 0.6, c_{11} = 5.9, c_{12} = 2.6, c_{13} = 2.2, c_{33} = 6.2, c_{44} = 1.6$; isotropic material - brass: $c_2 = 0.50, c_{11} = 3, c_{12} = 1, c_{13} = 1, c_{33} = 3, c_{44} = 0.9, /11/; n =$

$1/3, 1/5, 1/7; D = 1; m = -1, 0$ and 1 , respectively. Definite integrals in Eq.(21) are calculated by using Simpson's 1/3rd rule.

Curves are drawn between the creep stress distribution and displacement along with radii ratios $R = r/b$ (Figs. 2 and 3) for the rotating disc made of transversely isotropic material (i.e. magnesium and beryl), isotropic material (i.e. brass) having variable density parameter $m = -1, 0, 1$ and the angular speed $\Omega^2 = 75$ and 100 . From Figs. 2 and 3, the maximum value of radial stress occurs at the internal surface of isotropic material disc (i.e. brass) as that of transversely isotropic material disc (i.e. beryl and magnesium) for measure $n = 1/7$ ($N = 7$), but increases at measure values $n = 1/5$ and $1/3$, respectively. The value of circumferential stress decreases at the internal surface.

Values of radial, as well as hoop stress, increase with increasing density parameter and angular speed at the internal surface of the isotropic material disc in comparison to transversely isotropic disc. So, there is more possibility of fracture at the bore when the disc is of isotropic material with a higher angular speed as that of the disc being made of transversely isotropic material.

Curves are drawn in Fig. 4 between creep strain rates and radii ratio $R = r/b$ at $\Omega^2 = 75$; measures $n = 1/3, 1/5, 1/7$; density parameter $m = -1, 0, 1$ for isotropic material (i.e. brass), transversely isotropic (i.e. magnesium and beryl). From Fig. 4, we conclude that for the transversely isotropic material disc having measure $n = 1/3, 1/5, 1/7$ at $\Omega^2 = 75$ the required maximum values of strain rates are located at the internal surface. Further, strain rates values decrease with increased value of density parameter $m = -1, 0$ and 1 at angular speed $\Omega^2 = 75$.



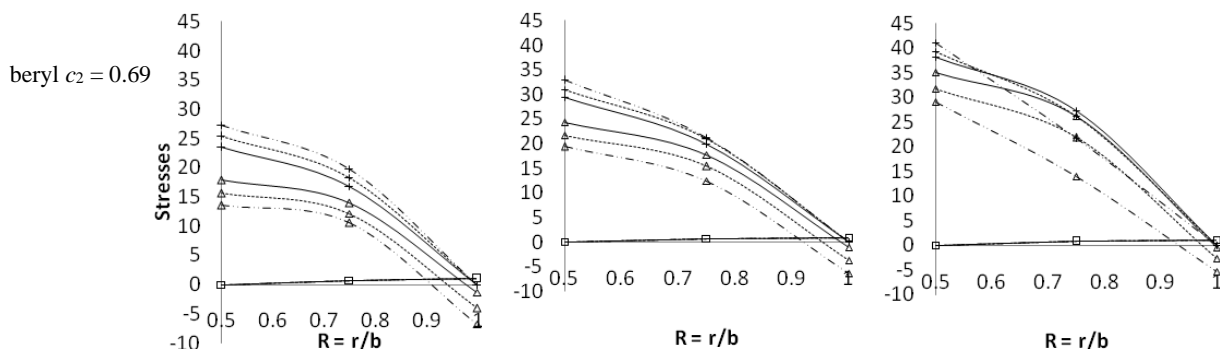


Figure 2. Stresses and displacement along radii ratios $R = r/b$ for transversely isotropic and isotropic materials at angular speed $\Omega^2 = 75$. (notation: $\sigma_r = \sigma_r$, $\sigma_\theta = \sigma_\theta$ and Displacement = u)

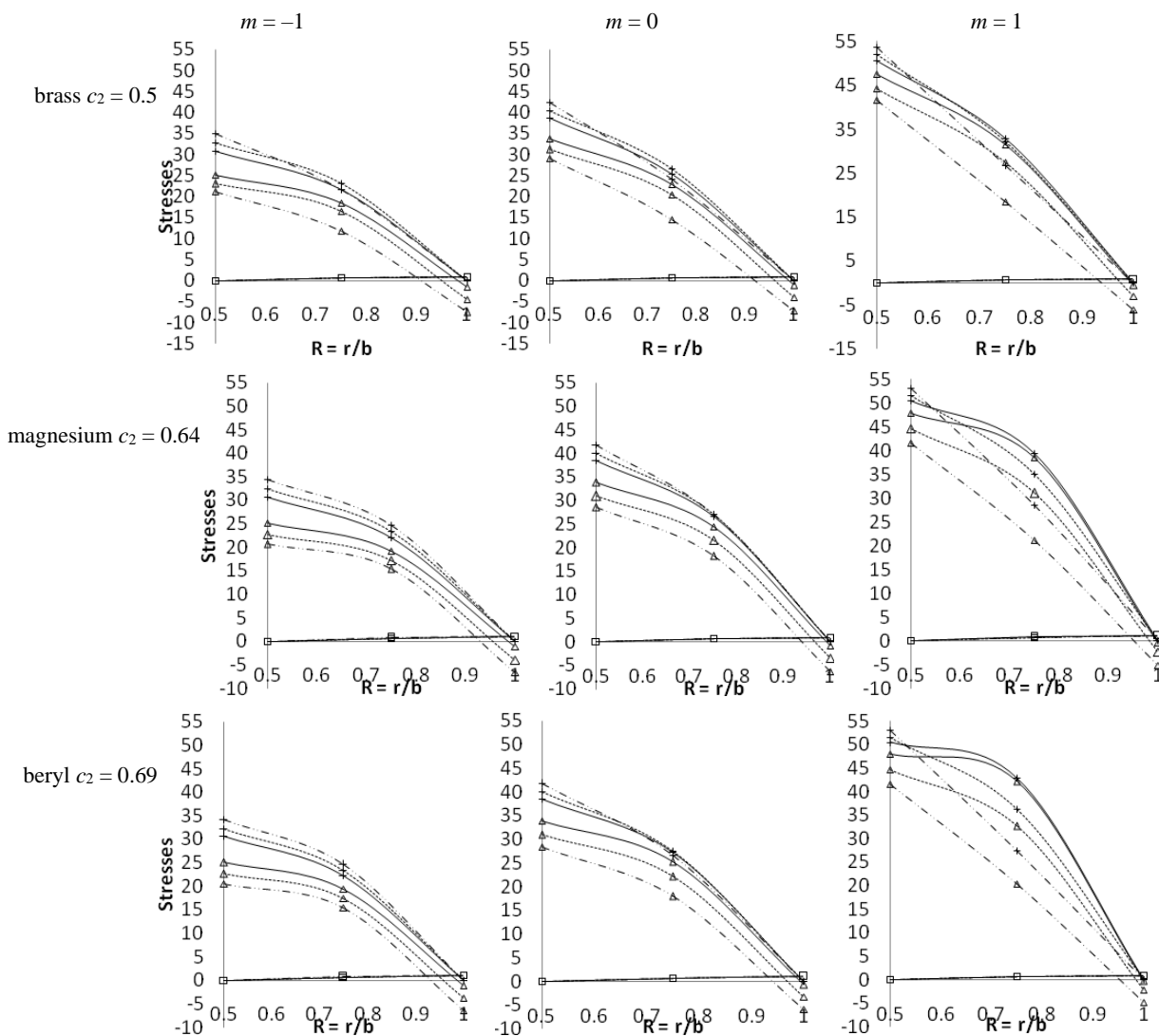


Figure 3. Stresses and displacement along radii ratios $R = r/b$ for transversely isotropic and isotropic materials at $\Omega^2 = 100$.

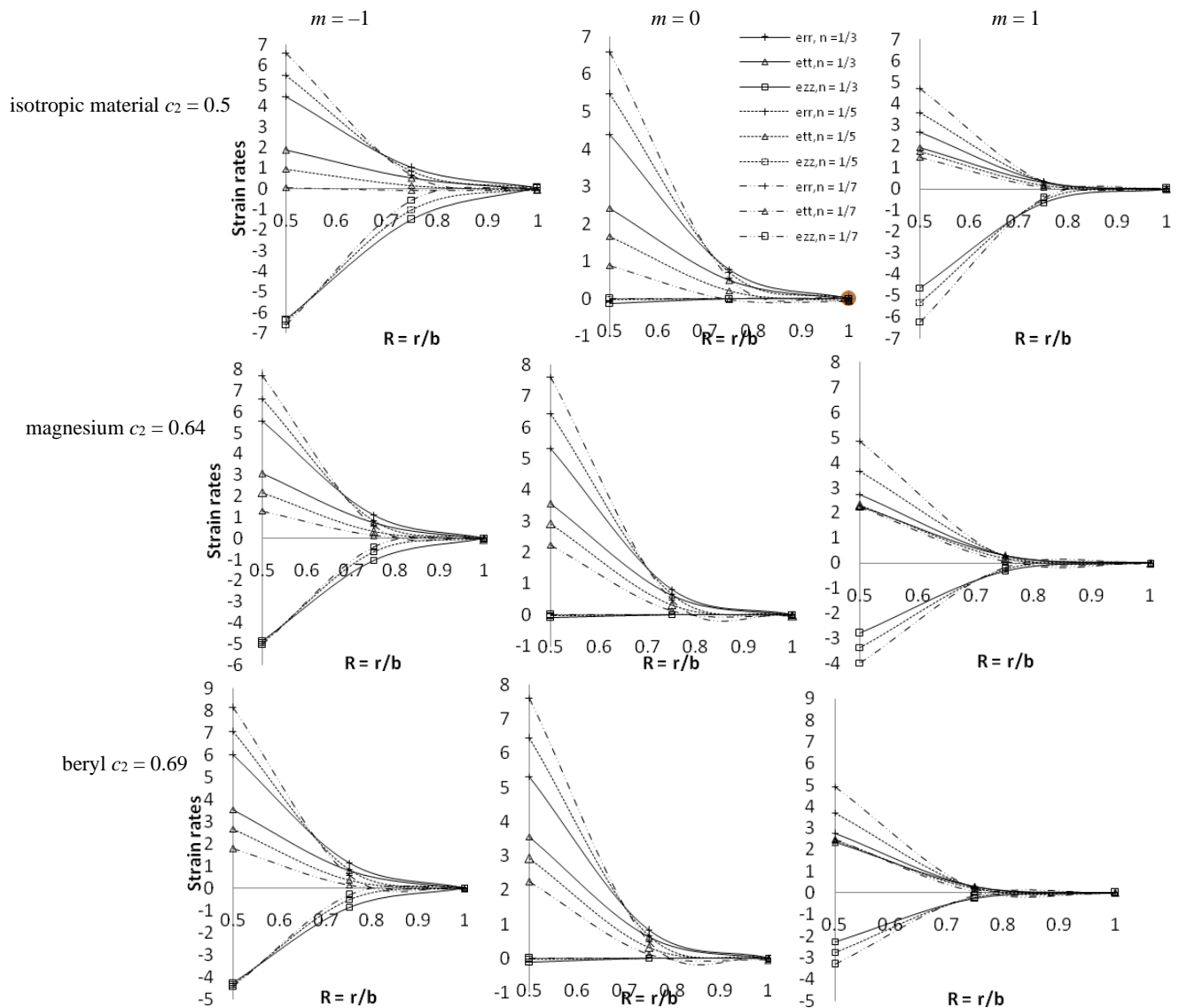


Figure 4. Strain rates in a rotating disc along radii ratios $R = r/b$ for transversely isotropic and isotropic material at angular speed $\Omega^2 = 75$. (notation: $err \equiv \epsilon_{rr}$, $ett \equiv \epsilon_{\theta\theta}$ and $ezz \equiv \epsilon_{zz}$)

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