Sukhvinder[1], Priya Gulial[2], Devinder Singh Pathania[3], Pankaj Thakur[4], Jatinder Kaur[5], Pushap Lata Sharma[6]*

COMPARATIVE STUDY OF CREEP IN A DISK MADE OF RUBBER/COPPER MATERIAL AND FITTED WITH RIGID SHAFT

UPOREDNO ISTRAŽIVANJE PUZANJA DISKA OD MATERIJALA GUMA/BAKAR U SKLOPU SA KRUTOM OSOVINOM

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Adresa autora / Author's address:
[1] Department of Mathematics, IKG Punjab Technical University Kapurthala, Jalandhar, Punjab, India
[2] Dept. of Mathematics, Faculty of Science and Technology, ICFAI University Himachal Pradesh, India 0009-0009-0266-2298
[3] Department of Mathematics, Guru Nanak Dev Engineering College, Ludhiana, Punjab, India
[4] Department of Mathematics, Faculty of Science and Technology, ICFAI University, Himachal Pradesh, India 0000-0001-8119-2697, *email: pankaj_thakur15@yahoo.co.in
[5] Department of Mathematics, Chandigarh University, Mohali, Punjab, India 0000-0003-3893-1356
[6] Department of Mathematics and Statistics, Himachal Pradesh University Summer Hill, Shimla, India

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Ključne reči
- disk
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Abstract

The article deals with the comparative study of creep analysis in a rotating disk made of rubber/copper material and fitted with rigid shaft. The effects of different pertinent parameters (i.e., angular speed and density) are considered for the rotating disk of rubber/steel material. The behaviour of creep stress/strain rate distribution, and density rise are investigated. From the obtained results, it is noticed that the radial stress requires a maximum value at the inner surface of the disk fitted with rigid shaft made of rubber material in comparison to the disk made of copper material. The strain rates must be decreased with increasing density parameter. Results have been discussed numerically and graphically.

Izvod

U radu je predstavljena uporedna analiza puzanja rotirajućeg diska izrađenog od materijala guma/bakar, u sklopu sa krutom osovinom. Razmatra se uticaj različitih relevantnih parametara (na pr. ugaona brzina i gustina) rotirajućeg diska od materijala guma/bakar. Proučeno je ponašanje raspodele napona i brzine deformacija usled puzanja, kao i porast gustine. Prema dobijenim rezultatima, primećuje se da je potrebna maksimalna vrednost radijalnog napona na unutrašnjoj površini diska u sklopu sa krutom osovinom, izrađenim od gume, u poređenju sa diskom od bakra. Brzina deformacije opada sa porastom parametra gustine. Data diskusija rezultata koji su predstavljeni numerički i grafički.

INTRODUCTION

The use of rotating disk in machinery, structural applications and chemical processing such as turbo generators, high speed gear engines, compressors, flywheels, steam turbine, sink fits, pumps, and computer disks, etc. The solutions for thin isotropic disk can be found in most of the standard creep textbooks /1-4/. Wahl /5/ discussed creep deformation in a disk by assuming small deformation, Tresca yield criterion, incompressibility condition and its associated flow rule and a power strain law. Donea et al. /6/ have investigated creep analysis of transversely isotropic bodies subjected to time dependent loading. Gupta et al. /7/ have investigated creep stresses and strain rates in a thin rotating disk with inclusion by using Seth's transition theory. Furthermore, Gupta et al. /8/ discussed thermo creep stresses and strain rate distribution in a thin rotating disk with shaft. It has been seen that radial stress has a maximum value at the inner surface of the disk made of incompressible material in comparison to the hoop stress and this value of radial stress further increases with increase of angular speed. Chekhov et al. /9/ studied the stress concentration in a transversely isotropic spherical shell with two circular rigid inclusions.

The objective of this paper is to investigate through numerical studies, creep stress and strain rate distribution in a rotating disk made of rubber/copper material fitted with shaft and having a variable density, by using transition theory and generalised strain measures. For a rotating disk with varying material properties, hoop/radial stress at the centre does not exceed the allowable value which tells the designers little more than that the design of the disk is safe. Thus, our prime objective is to calculate allowable creep stress and strain rate distribution in a rotating disk having variable density to incorporate a 'safety factor' that prevents disk fracture under density parameter. In the present study, we discuss the effect of creep stress/strain rate distribution versus radii ratio in a rotating disk made of isotropic material fitted with rigid shaft by using transition theory. The effect of creep stress/strain rates versus radii ratio and different angular speed/density parameter is discussed numerically and graphically.

MATHEMATICAL MODEL

For the purpose of analysis, we consider a disk made of rubber and copper materials having the inner and outer radii as a and b, respectively, and rotating with angular speed ω about an axis as shown in Fig. 1. The disk is assumed to have linearly varying density at any radius r expressed as:

$$\rho(r) = \rho_0 (r/b)^{-m}\,, \tag{1}$$

where: ρ_0 is the thickness at inner surface (say $r = b$); m is density parameter.

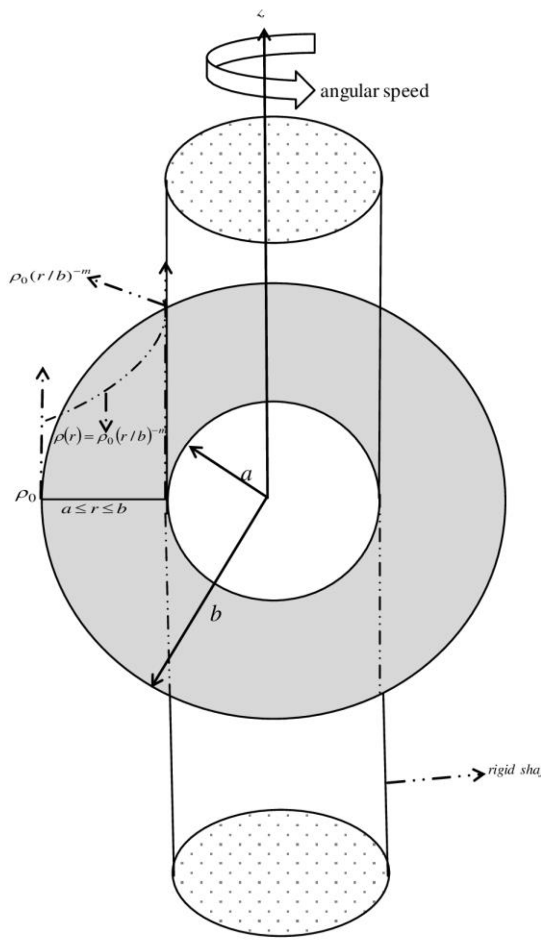

Figure 1 Geometrical configuration of disk

BASIC GOVERNING EQUATION

The displacement components in cylindrical polar co-ordinates are given by /10/,

$$u = r(1-\beta);\quad v = 0;\quad w = dz\,, \tag{2}$$

where: β is a function of $r = \sqrt{(x^2 + y^2)}$ only; and d is a constant. The stress components are given by /11/:

$$\tau_{rr} = \frac{2\mu}{n}\left[3-2c-\beta^n\left\{1-c+(2-c)(P+1)^n\right\}\right],$$
$$\tau_{\theta\theta} = \frac{2\mu}{n}\left[3-2c-\beta^n\left\{2-c+(1-c)(P+1)^n\right\}\right],$$
$$\tau_{r\theta} = \tau_{\theta z} = \tau_{zr} = \tau_{zz} = 0\,, \tag{3}$$

where: $r\beta' = \beta P$ and $c = 2\mu/(\lambda + 2\mu)$. Equations of equilibrium are given as:

$$\frac{d}{dr}(r\tau_{rr}) - \tau_{\theta\theta} + \rho\omega^2 r^2 = 0\,, \tag{4}$$

where: ρ is material density of the rotating disk.

Boundary condition: boundary conditions of the disk are taken as:

$$u = 0 \quad \text{at} \quad r = a, \quad \text{and} \quad \tau_{rr} = 0 \quad \text{at} \quad r = b \tag{5}$$

where: τ_{rr} is the stress along the radial direction of the disk made of isotropic materials.

Asymptotic solution at transition points: substituting Eq.(3) in Eq.(4) and after integration, we get the following nonlinear integro-differential equation:

$$(2-c)n\beta^{n+1}P(P+1)^{n-1}\frac{dP}{d\beta} = \frac{n\rho\omega^2 r^2}{2\mu} + \beta^n \times$$
$$\times\left[1-(P+1)^n - nP\left\{1-c+(2-c)(P+1)^n\right\}\right], \tag{6}$$

where: $r\beta' = \beta P$ (P is a function of β, and β is a function of r). Transition points P from Eq.(6) are $P \to -1$ and $P \to \pm\infty$.

SOLUTION OF THE PROBLEM

For finding creep stresses and strain rates, the transition function is taken through principal stress difference, see /7, 8, 10-25/ at transition point $P \to -1$. We define the transition function ζ as:

$$\zeta = \tau_{rr} - \tau_{\theta\theta} = \frac{2\mu\beta^n}{n}\left[1-(P+1)^n\right]. \tag{7}$$

By taking the logarithmic differentiation with respect to r of Eq.(7) and using Eq.(6), and taking the asymptotic value $P \to -1$, we get:

$$\frac{d}{dr}(\log\zeta) = \frac{1}{r(2-c)}\left\{n(3-2c) + 1 + \frac{n\rho\omega^2 r^{2+n}}{2\mu D^n}\right\}. \tag{8}$$

The asymptotic value of β as $P \to -1$ is D/r; D being a constant. Integrating Eq.(8) with respect to r, we get:

$$\zeta = \tau_{rr} - \tau_{\theta\theta} = Ar^k \exp(Fr^{n-m+2})\,, \tag{9}$$

where: A is a constant of integration; $\zeta = (1 - C)/(2 - C)$; $F = -\dfrac{n\rho_0\omega^2(3-2c)}{Eb^{-m}D^n(2-c)^2(n-m+2)}$; and $k = -\dfrac{n(3-2c)+1}{(2-c)}$.

From Eq.(7) and Eq.(9), we have

$$\tau_{rr} - \tau_{\theta\theta} = Ar^k \exp(Fr^{n-m+2})\,. \tag{10}$$

Substituting Eq.(10) in Eq.(4), we get:

$$\tau_{rr} = -A\int r^{k-1}\exp(Fr^{n-m+2})dr - \frac{\rho_0\omega^2 r^{2-m}}{(2-m)b^{-m}} + A_1\,, \tag{11}$$

where: A_1 is a constant of integration which can be determined by boundary condition. Using boundary condition Eq.(5) in Eq.(11), we get:

$$A_1 = -A\int_{r=b} r^{k-1}\exp(Fr^{n-m+2})dr - \frac{\rho_0\omega^2 b^2}{(2-m)}.$$

Substituting the value of A_1 in Eq.(11), we get:

$$\tau_{rr} = A\int_r^b r^{k-1}\exp(Fr^{n-m+2})dr + \frac{\rho_0\omega^2(b^{2-m} - r^{2-m})}{(2-m)b^{-m}}. \tag{12}$$

Substituting Eq.(12) in Eq.(10), we get:

$$\tau_{\theta\theta} = A\left[\int_r^b r^{k-1}\exp(Fr^{n-m+2})dr - r^k\exp(Fr^{n-m+2})\right] +$$
$$+\frac{\rho_0\omega^2(b^{2-m} - r^{2-m})}{(2-m)b^{-m}}. \tag{13}$$

Investigation displacement: taking the asymptotic value $P \to -1$ from Eq.(9) and Eq.(10), we get:

$$\beta = \left[\frac{Ar^k \exp(Fr^{n-m+2}) n(3-2c)}{E(2-c)} \right]^{1/n} . \qquad (14)$$

Using Eq.(14) in Eq.(1), we get:

$$u = r - r\left[\frac{Ar^k \exp(Fr^{n-m+2}) n(3-2c)}{E(2-c)} \right]^{1/n} . \qquad (15)$$

Using boundary condition Eq.(5) in Eq.(15), we get:

$$A = \frac{E(2-c)}{a^k \exp(Fa^{n-m+2}) n(3-2c)} .$$

Substituting the value of A in Eqs.(12), (13), and (15), we get:

$$\tau_{rr} = \frac{E(2-c)}{a^k \exp(Fa^{n-m+2}) n(3-2c)} \int_r^b r^{k-1} \exp(Fr^{n-m+2}) dr + \frac{\rho_0 \omega^2 (b^{2-m} - r^{2-m})}{(2-m) b^{-m}} ,$$

$$\tau_{\theta\theta} = \frac{E(2-c)}{a^k \exp(Fa^{n-m+2}) n(3-2c)} \left[\int_r^b r^{k-1} \exp(Fr^{n-m+2}) dr - r^k \exp(Fr^{n-m+2}) \right] + \frac{\rho_0 \omega^2 (b^{2-m} - r^{2-m})}{(2-m) b^{-m}} ,$$

$$u = r - r\left[\left(\frac{r}{a}\right)^k \frac{\exp(Fr^{n-m+2})}{\exp(Fa^{n-m+2})} \right]^{1/n} . \qquad (16)$$

Equation (16) gives creep stresses and displacement for a thin rotating disk.

Non-dimensional quantities: non-dimensional quantities are defined as $R = r/b$, $R_0 = a/b$, $\sigma_r = \tau_{rr}/E$, $\sigma_\theta = \tau_{\theta\theta}/E$, $\Omega^2 = \rho\omega^2 b^2/E$, and $U = u/b$. Equation (16) in non-dimensional form becomes:

$$\sigma_r = \frac{1}{R_0^k \exp(F_1 R_0^{n-m+2}) n(1+\nu)} \int_R^1 R^{k-1} \exp(F_1 R^{n-m+2}) dR + \frac{\Omega^2 (1-R^{2-m})}{(2-m)} ,$$

$$\sigma_\theta = \frac{1}{R_0^k \exp(F_1 R_0^{n-m+2}) n(1+\nu)} \int_R^1 R^{k-1} \exp(F_1 R^{n-m+2}) dR - R^k \exp(F_1 R^{n-m+2}) + \frac{\Omega^2 (1-R^{2-m})}{(2-m)} ,$$

$$U = R - R\left[\frac{R^k \exp(F_1 R^{n-m+2})}{R_0^k \exp(F_1 R_0^{n-m+2})} \right]^{1/n} . \qquad (17)$$

Fully-plastic stage: for a fully-plastic stage (say $\nu \to 1/2$) Eq.(17) becomes:

$$\sigma_r = \frac{2}{R_0^{k_1} \exp(F_2 R_0^{n-m+2}) 3n} \int_R^1 R^{k_1-1} \exp(F_3 R^{n-m+2}) dR + \frac{\Omega^2 (1-R^{2-m})}{(2-m)} ,$$

$$\sigma_\theta = \frac{2}{R_0^{k_1} \exp(F_1 R_0^{n-m+2}) 3n} \left[\int_R^1 R^{k_1-1} \exp(F_3 R^{n-m+2}) dR - R^{k_1} \exp(F_3 R^{n-m+2}) \right] + \frac{\Omega^2 (1-R^{2-m})}{(2-m)} ,$$

$$U = R - R\left[\frac{R^{k_1} \exp(F_3 R^{n-m+2})}{R_0^{k_1} \exp(F_3 R_0^{n-m+2})} \right]^{1/n} , \qquad (18)$$

where: $F_3 = -\frac{3n\Omega^2 b^n}{4D^n (n-m+2)}$; $k_1 = -\frac{3n+1}{2}$.

VALIDATION OF RESULTS

By taking $m \to 0$ in Eq.(17), we get:

$$\sigma_r = \frac{1}{R_0^k \exp(F_1 R_0^{n+2}) n(1+\nu)} \int_R^1 R^{k-1} \exp(F_1 R^{n+2}) dR + \frac{\Omega^2 (1-R^2)}{2} ,$$

$$\sigma_\theta = \frac{1}{R_0^k \exp(F_1 R_0^{n+2}) n(1+\nu)} \left[\int_R^1 R^{k-1} \exp(F_1 R^{n+2}) dR - R^k \exp(F_1 R^{n+2}) \right] + \frac{\Omega^2 (1-R^2)}{2} ,$$

$$U = R - R\left[\frac{R^k \exp(F_1 R^{n+2})}{R_0^k \exp(F_1 R_0^{n+2})} \right]^{1/n} , \qquad (19)$$

where: $F_4 = -\frac{n\Omega^2 (1-\nu^2) b^n}{D^n (n+2)}$.

Fully-plastic stage: Eq.(18) becomes:

$$\sigma_r = \frac{2}{R_0^{k_1} \exp(F_2 R_0^{n+2}) 3n} \int_R^1 R^{k_1-1} \exp(F_3 R^{n+2}) dR + \frac{\Omega^2 (1-R^2)}{2} ,$$

$$\sigma_\theta = \frac{2}{R_0^{k_1} \exp(F_1 R_0^{n+2}) 3n} \left[\int_R^1 R^{k_1-1} \exp(F_3 R^{n+2}) dR - R^{k_1} \exp(F_3 R^{n+2}) \right] + \frac{\Omega^2 (1-R^2)}{2} ,$$

$$U = R - R\left[\frac{R^{k_1} \exp(F_3 R^{n+2})}{R_0^{k_1} \exp(F_3 R_0^{n+2})} \right]^{1/n} , \qquad (20)$$

where: $F_5 = -\frac{3n\Omega^2 b^n}{4D^n (n+2)}$. The results obtained from Eqs. (19)-(20) are the same as in Gupta et al. /7/.

Estimation of strain rates: strain rates are given by /8/:

$$\dot{\varepsilon}_{rr} = F_6 (\sigma_r - \nu\sigma_\theta) ,$$
$$\dot{\varepsilon}_{\theta\theta} = F_6 (\sigma_\theta - \nu\sigma_r) ,$$
$$\dot{\varepsilon}_z = -\nu F_6 (\sigma_\theta + \sigma_r) , \qquad (21)$$

where: $F_6 = \left[n(1+\nu)(\sigma_r - \sigma_\theta) \right]^{1/n-1}$.

NUMERICAL RESULTS AND DISCUSSION

To see the combined effect of creep stress and strain rate distribution in a rotating disk made of isotropic material, say rubber (Poisson's ratio $\nu = 0.5$), and copper material (Poisson's ratio $\nu = 0.333$), /8/. The following numerical values are taken: $\Omega^2 = \rho_0\omega^2 b^2/E = 35, 65$; $m = -1.4, 0, 1.4$;

a = 1; b = 2; D = 1, and n = 1/3, 1/5 (i.e., N = 3, 5), in respect. In classical theory the measure N is equal to $1/n$. Definite integrals in Eq.(17) are solved by using Simpson's rule. In Figs. 2 and 3, curves are drawn between dimensionless creep stress distribution (i.e., σ_r, σ_θ) versus radii ratio $R = r/b$ for a rotating disk of isotropic material (say rubber/copper) having variable density m = -1.4, 0, 1.4, Poisson ratio ν = 0.5 (say rubber material) and ν = 0.333 (say copper material). It is observed that radial stress has a maximum at the inner surface of the disk as compared to the hoop stress. It can also be noticed that the radial stress requires maximum value at the inner surface of the disk fitted with rigid shaft made of rubber material in comparison to the disk made of copper for measure n = 1/5 or (N = 5) at angular speed Ω^2 = 35, whereas hoop stress requires maximum value at the inner surface for measure n = 1/3 or (N = 3) at this angular speed. Values of hoop/radial stress further increase at the internal surface with increase in angular speed (say Ω^2 = 65) for measure n = 1/5 and 1/3, or (N = 5, 3), respectively.

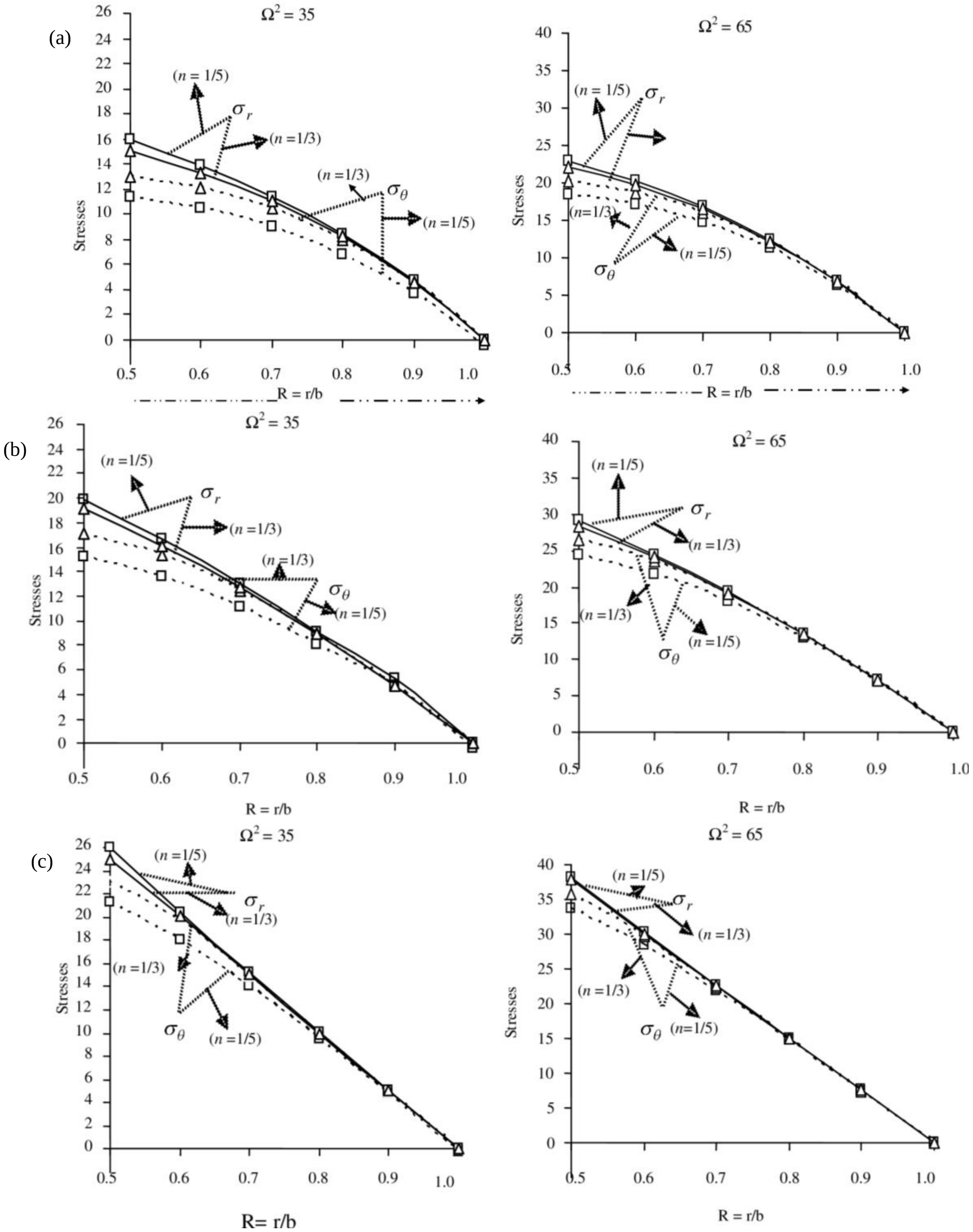

Figure 2. Graphical comparisons between dimensionless creep stress distribution vs. radii ratio $R = r/b$ and having variable density: a) m = -1.4; b) m = 0 ; c) m = 1.4, and Poisson ratio ν = 0.5.

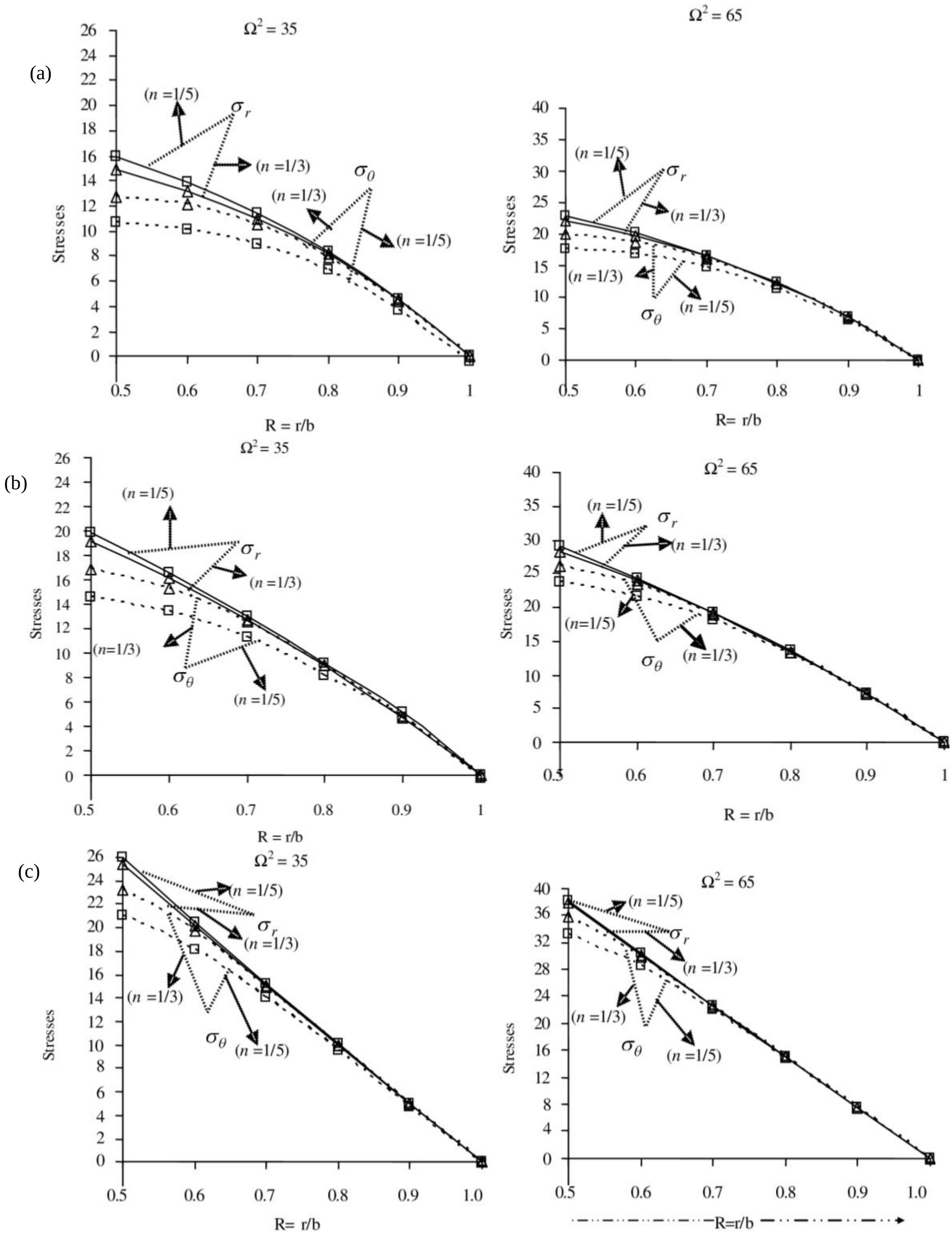

Figure 3. Graphical results between non-dimensionless creep stress distribution vs. radii ratio $R = r/b$ and having variable density: a) m = -1.4; b) m = 0 ; c) m = 1.4, and Poisson ratio ν = 0.333.

From Figs. 3 and 4, it is seen that with the introduction of density parameter the values of radial/hoop stress must be decreased at the inner surface of a disk, as described by Rimrott /26/, if a material tends to fracture by cleavage. It's likely to begin as a sub-surface fracture close to the bore of the disk, because the largest tensile stress occurs at this location. This means that for a disk rotating with higher angular speed and whose density increases radially, the possibility of fracture at the bore decreases, whereas for a disk whose density decreases radially, the possibility of fracture at the bore increases. The disk made of rubber material is more comfortable than the disk of a copper material. Figure 4 demonstrates the behaviour of dimensionless strain rate distribution versus radii ratio $R = r/b$ at angular speed Ω^2 = 35, 65, and measure n = 1/5 or (N = 5). It is observed that the disk of copper material requires a maximum value of strain rates at the inner surface as compared to the disk of rubber material for measure n = 1/5 (or N = 5) at angular speed Ω^2 = 35. With increasing angular speed (say Ω^2 = 65), the values of strain rates further increase at the inner surface of the disk of rubber/copper material for measure n = 1/3 (or N = 3), respectively. Furthermore, the strain rates must decrease with increasing density parameter.

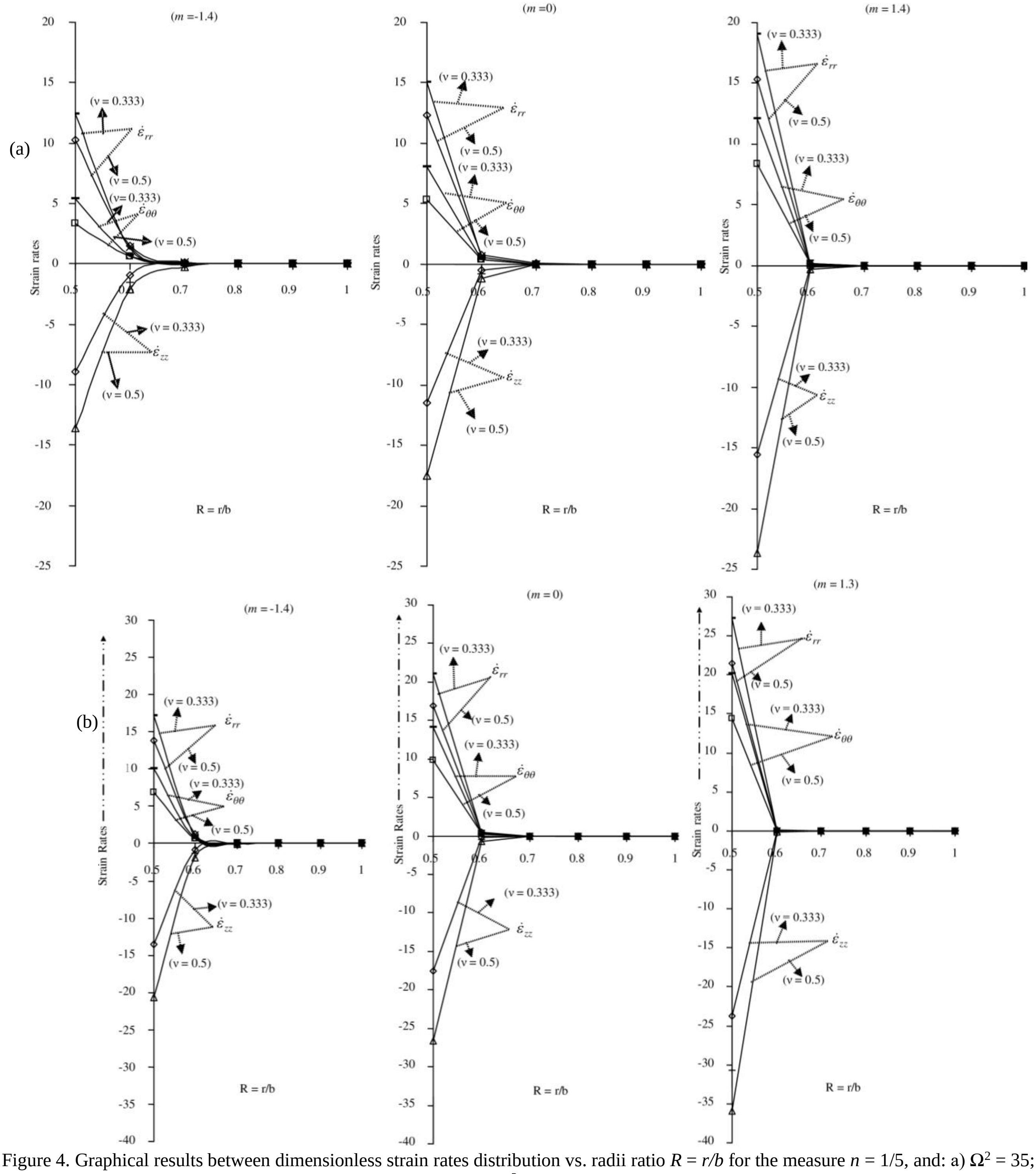

Figure 4. Graphical results between dimensionless strain rates distribution vs. radii ratio $R = r/b$ for the measure n = 1/5, and: a) Ω^2 = 35; b) Ω^2 = 65.

CONCLUSIONS

The main findings are given as follows.

- The radial stress has a maximum at the inner surface of the disk as compare to the hoop stress.
- It is also noticed that the radial stress requires a maximum value at the inner surface of the disk fitted with rigid shaft made of rubber material in comparison to the disk made of copper material.

– With the introduction of density parameter, the values of radial/hoop stress must be decreased at the inner surface of a disk.
– The copper material disk requires a maximum value of strain rates at the inner surface in comparison to the rubber material disk.
– Results for /7/ can be obtained by taking $m \rightarrow 0$ in the resulting equations.

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