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MODELLING OF CREEP BEHAVIOUR OF A ROTATING DISC IN THE PRESENCE OF LOAD AND VARIABLE THICKNESS BY USING SETH TRANSITION THEORY

MODELIRANJE PUZANJA ROTIRAJUĆEG DISKA SA OPTEREĆENJEM I PROMENLJIVOM DEBLJINOM PRIMENOM TEORIJE PRELAZNIH NAPONA SETA

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- strain rates
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- disc

Ključne reči
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- ugaona brzina
- opterećenje
- disk

Abstract

The purpose of this paper is to present study of creep behaviour of a rotating disc in the presence of load and thickness by using Seth's transition theory. It has been observed that a flat rotating disc made of compressible as well as incompressible material with load E_1 = 10, increases the possibility of fracture at the bore. It Is also shown that a rotating disc of incompressible material and thickness that increases radially experiences higher creep rates at the internal surface in comparison to a disc of compressible material. The model proposed in this paper is used in mechanical and electronic devices. They have extensive practical engineering applications such as in steam and gas turbines, turbo generators, flywheel of internal combustion engines, turbojet engines, reciprocating engines, centrifugal compressors and brake discs.

Izvod

U radu je predstavljena studija puzanja rotirajućeg diska datog opterećenja i debljine primenom Setove teorije prelaznih napona. Uočeno je da ravan rotirajući disk napravljen od stišljivog, odnosno, nestišljivog materijala sa opterećenjem E_1 = 10, povećava mogućnost pojave loma na otvoru. Takođe je pokazano da rotirajući disk od nestišljivog materijala, sa radijalnim porastom debljine povećanje ima veću brzinu puzanja na unutrašnjoj površini, u odnosu na disk napravljen od stisljivog materijala. Model predložen u ovom radu se koristi u mehaničkim i električnim uređajima i ima širu praktičnu primenu, na primer, parne i gasne turbine, turbogeneratori, zamajac motora sa unutrašnjim sagorevanjem, turbomlazni motori, klipni motori, centrifugalni kompresori i kočioni diskovi.

INTRODUCTION

Machine components in most sophisticated equipment and automated industry line machines are under the persistent influence of centrifugal force. These machine components may be in the form of solid, annular discs, gears, plates, crank-shafts, ball bearings, solid or hollow tubular structures etc. Being in the continuous state of stress, no matter what kind of material these components are made of, there is a likely deformation in their structure. Designers of such machines have always tried to use specific materials in their manufacture pertaining to the kind of stress they will experience in the fully functional system. Isotropic, anisotropic and orthotropic materials have been used from time to time in their manufacture. The description of their deformation is given by a different set of equations for elastic, plastic and creep state and can be found in standard textbooks, /4-8, 11/. Gupta *et al.* /9/ analysed creep transition in a thin rotating disc with rigid inclusion by using the Seth transition theory. Thakur /15, 26/ investigated creep transition stresses in a thin rotating disc with a shaft by finite deformation under steady state temperature, by using Seth theory and further extended his investigations on thermal creep stresses and strain rates in a circular disc with a shaft having variable density. Seth transition theory utilizes the concept of generalized strain measure and asymptotic solution at critical points or turning points of the differential equations defining the field, and has been successfully applied to a large number of problems /2, 3, 9, 12, 15-36/.

Seth /2/ has defined the generalized principal strain measure as:

$$e_{ii} = \int_0^{\overset{A}{e}_{ii}} \left(1 - 2\overset{A}{e}_{ii}\right)^{\frac{n}{2}-1} d\overset{A}{e}_{ii} = \frac{1}{n}\left[1 - \left(1 - 2\overset{A}{e}_{ii}\right)^{n/2}\right], \quad (1)$$

where: n is the measure; and $\overset{A}{e}_{ii}$ are principal Almansi finite strain components. The disc thickness is assumed to vary along the radius in the form:

$$H = H_0 (r/b)^{-k} \tag{2}$$

where: H_0 is the thickness at $r = b$; and k is the thickness parameter. In this paper, we investigate creep behaviour of a rotating disc in the presence of load and thickness by using Seth's transition theory. Results are discussed and depicted graphically.

GOVERINING EQUATIONS

Consider a thin rotating disc of variable thickness with a central bore of inner radius a and outer radius b, respectively. The disc is rotating with angular speed ω of gradually increasing magnitude about an axis perpendicular to its plane and passing through the centre. The density of the disc is assumed to be constant and is taken sufficiently small so that the disc is effectively in a state of plane stress, that is, the axial stress T_{zz} is zero.

Displacement coordinate: the displacement components in cylindrical coordinate are given by /3/:

$$u = r(1-\beta),\ v = 0,\ w = dz\ , \tag{3}$$

where: u, v, w are displacement components; β is position function, depending on $r = \sqrt{x^2+y^2}$ only; and d is a constant. Finite components of strain are given by /3/ as:

$$\begin{aligned} &\overset{A}{e}_{rr} = \frac{1}{2}\left[1-(r\beta'+\beta)^2\right],\ \ \overset{A}{e}_{\theta\theta} = \frac{1}{2}[1-\beta^2], \\ &\overset{A}{e}_{zz} = \frac{1}{2}\left[1-(1-d)^2\right],\ \ \overset{A}{e}_{r\theta} = \overset{A}{e}_{\theta z} = \overset{A}{e}_{zr} = 0. \end{aligned} \tag{4}$$

where: $\beta' = d\beta/dr$. Substituting Eq.(4) into Eq.(1), the generalized components of strain are given:

$$\begin{aligned} &e_{rr} = \frac{1}{n}\left[1-(r\beta'+\beta)^n\right],\ \ e_{\theta\theta} = \frac{1}{n}\left[1-\beta^n\right], \\ &e_{zz} = \frac{1}{n}\left[1-(1-d)^n\right],\ \ e_{r\theta} = e_{\theta z} = e_{zr} = 0 \end{aligned} \tag{5}$$

where: r, θ, z are polar coordinates; and $\beta' = d\beta/dr$.

Stress-strain relation: stress-strain relations for isotropic material are given by /1/:

$$T_{ij} = \lambda\delta_{ij} I_1 + 2\mu e_{ij}\quad (i, j = 1,\ 2,\ 3) \tag{6}$$

where: T_{ij} and e_{ij} are the stress, strain components; λ and μ are Lame's constants; $I_1 = e_{kk}$ is the first strain invariant; δ_{ij} is the Kronecker's delta. Using Eq.(5) in Eq.(6), the stress components are obtained as:

$$\begin{aligned} &T_{rr} = \left(\frac{2\mu}{n}\right)\left[3-2c-\beta^n\left\{(1-c)+(2-c)(P+1)^n\right\}\right], \\ &T_{\theta\theta} = \left(\frac{2\mu}{n}\right)\left[3-2c-\beta^n\left\{(2-c)+(1-c)(P+1)^n\right\}\right], \\ &T_{r\theta} = T_{\theta z} = T_{zr} = T_{zz} = 0 \end{aligned} \tag{7}$$

where: P (*i.e.* function of β, and β is the function of r); and c is the compressibility factor of the material.

Equation of equilibrium: the equilibrium equations for the rotating disc are given by:

$$r\frac{d}{dr}(HT_{rr}) + H(T_{rr} - T_{\theta\theta}) + \rho\omega^2 r^2 H = 0 \tag{8}$$

where: ρ is the constant material density; ω is angular speed; T_{rr} and $T_{\theta\theta}$ are the radial and circumferential stress of the disc.

Critical points or turning points: substituting Eq.(7) and Eq.(2) into Eq.(8), we get a nonlinear differential equation in β as:

$$\begin{aligned} &(2-C)n\beta^{n+1}P(P+1)^{n-1}\frac{dP}{d\beta} = \left(\frac{rH'}{H}\right)\Big[3-2c-\beta^n\{1-c+ \\ &+(2-c)(P+1)^n\}\Big] + \beta^n\Big\{1-(P+1)^n - nP\big[1-C+(2-C)\times \\ &\times(P+1)^{nn}\big]\Big\} + \frac{n\rho\omega^2 r^2}{2\mu} \end{aligned} \tag{9}$$

where: $r\beta' = \beta P$. Turning points of β in Eq.(9) are $P \to \pm\infty$, $P \to -1$, $P \to -1$.

Boundary conditions: the boundary condition is:

$$T_{rr} = 0\ \text{ at }\ r = a\ \text{ and }\ T_{rr} = T_0\ \text{ at }\ r = b. \tag{10}$$

where: T_0 is the applied load at the external surface of the rotating disc.

SOLUTION OF THE PROBLEM

Several authors solved many problems of the disc by using different methods. Hojjati *et al.* /13/ applied theoretical and numerical methods for stress-strain analysis of rotating disc with non-uniform thickness and density subjected to only centrifugal body loadings. They employed elastic-linear strain hardening material to analyse the rotating disc by VMP, Runge-Kutta's and Finite element methods. Hojjati *et al.* /10, 13, 14/ solved the elastic-plastic problem of the disc by using Variational iteration method, Homotopy perturbation method, and a Domain decomposition method. In this paper, we apply the Seth method to solve creep deformation in the disc. For finding the creep deformation, the transition function is taken through principal stress difference (see /2, 3, 9, 12, 15-36/) at the turning point $P \to -1$. We define the transition function $\Im$ as:

$$\Im = T_{rr} - T_{\theta\theta} = \frac{2\mu\beta^n}{n}\left[1-(P+1)^n\right] \tag{11}$$

where: $\Im$ is a function of r only.

By taking the logarithmic differentiation of Eq.(11) with respect to r and using Eq.(9) and taking the asymptotic value $P \to -1$, we get:

$$\begin{aligned} \frac{d}{dr}(\ln\Im) = &-\left[\frac{n(3-2c)+1}{r(2-C)}\right] + \frac{H'}{H}\nu - \frac{r^n}{D^n(2-c)}\times \\ &\times\left[\frac{H'}{H}(3-2c) + \frac{n\rho\omega^2 r^2}{2\mu}\right] \end{aligned} \tag{12}$$

where: $\nu = 1 - c/2 - c$ is the Poisson ratio.

Asymptotic value of β as $P \to -1$ is D/r and D being a constant. Integrating Eq.(12) with respect to r, we get

$$\Im = T_{rr} - T_{\theta\theta} = A r^{B} h^{\nu} \exp F \,, \tag{13}$$

where: A is a constant of integration, which can be determined by using boundary conditions and

$$B = -\frac{n(3-2c)+1}{(2-c)} \text{ and}$$

$$F = -\frac{1}{(2-c)D^{n}} \int \left[(3-2c)\frac{h'}{h} + \frac{n\rho\omega^{2} r}{2\mu} \right] r^{n}\, dr \,.$$

Using Eqs.(13) and (8), we get:

$$HT_{rr} = A_1 - A\int F dr - \rho\omega^2 \int rH dr \tag{14}$$

where: A_1 is a constant of integration; and $F_1 = r^{B_1-1}H^{\nu+1}\exp F$. By using Eq.(10) into Eq.(14), we get

$$A = -\left[\rho\omega^{2} \int_a^b rH dr + H_0 T_0 \right] / \int_a^b F_1 dr,$$

$$A_1 = \rho\omega^2 \int_{r=a} H dr + A \int_{r=a} F_1 dr .$$

Substituting the value of constants A and A_1 into Eq.(14),

$$T_{rr} = \rho\omega^2 \int_a^b H r dr + H_0 T_0 \frac{\int_a^r F_1 dr}{\int_a^b F_1 dr} - \frac{\rho\omega^2}{H} \int_a^r H r dr \,. \tag{15}$$

Using Eq.(15) in Eq.(13),

$$T_{\theta\theta} = T_{rr} + \frac{\rho\omega^2 \int_a^b H r dr + H_0 T_0}{\int_a^b F_1 dr} \left(\frac{r F_1}{H} \right). \tag{16}$$

Non-dimensional components: we introduce the following non-dimensional components: $R = r/b$, $R_0 = a/b$, $\sigma_r = T_{rr}/E$, $\sigma_\theta = T_{\theta\theta}/E$, $E_1 = T_0/E$ and $\Omega^2 = \rho\omega^2 b^2/E$. Creep transitional stresses, Eqs.(15) and (16), in non-dimensional form become:

$$\sigma_r = \left[\Omega^2 \left(\frac{1-R_0^{2-k}}{2-k} \right) + E_1 \right] \frac{R^k \int_{R_0}^{R} F_2 dR}{\int_{R_0}^{1} F_2 dR} - \frac{\Omega^2 R^k (R^{2-k} - R_0^{2-k})}{(2-k)} \tag{17}$$

$$\sigma_\theta = \sigma_r + \left[\Omega^2 \left(\frac{1-R_0^{2-k}}{2-k} \right) + E_1 \right] \frac{R^k R^{B-k(\nu+1)} b^B}{\int_{R_0}^{1} F_2 dR} \exp F_2 \tag{18}$$

where: $F_1 = \dfrac{kb^n (3-2c) R^n}{n(2-c)D^n} - \dfrac{n(3-2c)\Omega^2 b^n R^{2+n}}{E_1 (2-c)^2 D^n (2+n)}$ and when $F_2 = R^{B-1-k(\nu+1)} b^{B-1} \exp F_1$.

The disc made of incompressible material ($\nu \to 1/2$ or $C = 0$), Eqs.(17) and (18) become:

$$\sigma_r = \frac{\left[\Omega^2 \left(\frac{1-R_0^{2-k}}{2-k} \right) + E_1 \right]}{\int_{R_0}^{1} F_4 dR} R^k \int_{R_0}^{R} F_4 dR - \frac{\Omega^2 R^k (R^{2-k} - R_0^{2-k})}{(2-k)} \tag{19}$$

$$\sigma_\theta = \sigma_r + \frac{\left[\Omega^2 \left(\frac{1-R_0^{2-k}}{2-k} \right) + E_1 \right]}{\int_{R_0}^{1} F_4 dR} R^k R^{B_1 - k(\nu+1)} b^{B_1} \exp F_3 \tag{20}$$

where: $F_3 = \dfrac{3kb^n R^n}{2nD^n} - \dfrac{3n\Omega^2 b^n R^{2+n}}{4E_1 D^n (2+n)}$; $B_1 = -\left[\dfrac{3n+1}{2} \right]$; and $F_4 = R^{-1.5(n+k+1)} b^{-1.5(n+1)} \exp F_3$, are constants.

CREEP DEFORMATION PARAMETER

When the creep sets in, the strains should be replaced by strain rates. The stress-strain, /1/, becomes:

$$\dot{e}_{ij} = \frac{1+\nu}{E} T_{ij} - \frac{\nu}{E} \delta_{ij} T \,, \tag{21}$$

where: e_{ij} is the strain rate tensor with respect to flow parameter t and $T = T_{ii}$ be first stress invariant and $\nu = (1 - C)/(2 - C)$ is Possion's ratio. Differentiating Eq.(5) *w.r.t.* time, t,

$$\dot{e}_{\theta\theta} = -\beta^{n-1} \dot{\beta} \,. \tag{22}$$

For SWAINGER measure (i.e. $n = 1$), Eq.(21)) becomes:

$$\dot{\varepsilon}_{\theta\theta} = \dot{\beta} \,, \tag{23}$$

where: $\dot{\varepsilon}_{\theta\theta}$ is the SWAINGER strain measure. From Eq.(11) the transition value β is given at transition point $P \to -1$ by:

$$\beta = (n/2\mu)^{1/n} \left[T_{rr} - T_{\theta\theta} \right]^{1/n} . \tag{24}$$

Using Eqs.(22), (23) and (24) in Eq.(21), we get

$$\dot{\varepsilon}_{rr} = \eta[\sigma_r - \nu\sigma_\theta] \,, \dot{\varepsilon}_{\theta\theta} = \eta[\sigma_\theta - \nu\sigma_r] \,, \dot{\varepsilon}_{\varphi\varphi} = -\eta\nu(\sigma_r + \sigma_\theta) \tag{25}$$

where: $\dot{\varepsilon}_{rr}$, $\dot{\varepsilon}_{\theta\theta}$ and $\dot{\varepsilon}_{zz}$ are strain rate tensor, and $\eta = \left[n(\sigma_r - \sigma_\theta)(1+\nu) \right]^{\frac{1}{n}-1}$.

For fully plastic states ($\nu \to$ 1/2 or $C = 0$), Eq.(25) becomes:

$$\dot{\varepsilon}_{rr} = \eta_1 \left[\sigma_r - \frac{1}{2}\sigma_\theta \right] , \dot{\varepsilon}_{\theta\theta} = \eta_1 \left[\sigma_\theta - \frac{1}{2}\sigma_r \right] , \dot{\varepsilon}_{\varphi\varphi} = -\frac{\eta_1}{2}(\sigma_r + \sigma_\theta) \tag{26}$$

where: $\eta_1 = \left[\dfrac{3n}{2}(\sigma_r - \sigma_\theta) \right]^{\frac{1}{n}-1}$.

These constitutive equations are same as obtained by /4/ for finding the creep stresses, provided we put $n = 1/N$ and N be the measure.

NUMERICAL ILLUSTRATION AND DISCUSION

For calculating creep strain rates based on the above analysis, the following values have been taken $\Omega^2 = 10, 50$; $n = 1/3, 1/5, 1/7$ (i.e. $N = 3, 5, 7$); $\nu = 0.5$ (incompressible material), i.e. rubber /1/; $\nu = 0.3$ (compressible materials, i.e. copper, /1/); $k = 0, 0.5, 0.7$, $E_1 = 0.01, 10$; and $D = 1$. Definite integrals in Eqs.(17) and (18) have been solved by using Simpson's 1/3rd rule. Curves are drawn between stresses and radii ratio $R = r/b$ (see Figs. 1-3) for the rotating disc made of compressible as well as incompressible material, having variable thickness and different angular speed. For $E_1 = 0.01$, as seen from Fig. 1 the circumferential stress is maximal at the internal surface of flat disc ($k = 0$) made of compressible material for measure $n = 1/3$ (or $N = 3$) at different angular speed. The value of this circumferential stress decreases for measure $n = 1/5$, $1/7$ (or $N = 5$, 7). For $E_1 = 10$, as seen from Fig. 1 the circumferential stress has much higher values at the internal surface in comparison to $E_1 = 0.01$. It means that a flat disc made of compressible as well as incompressible material with load $E_1 = 10$, has an increased possibility of fracture at the bore.

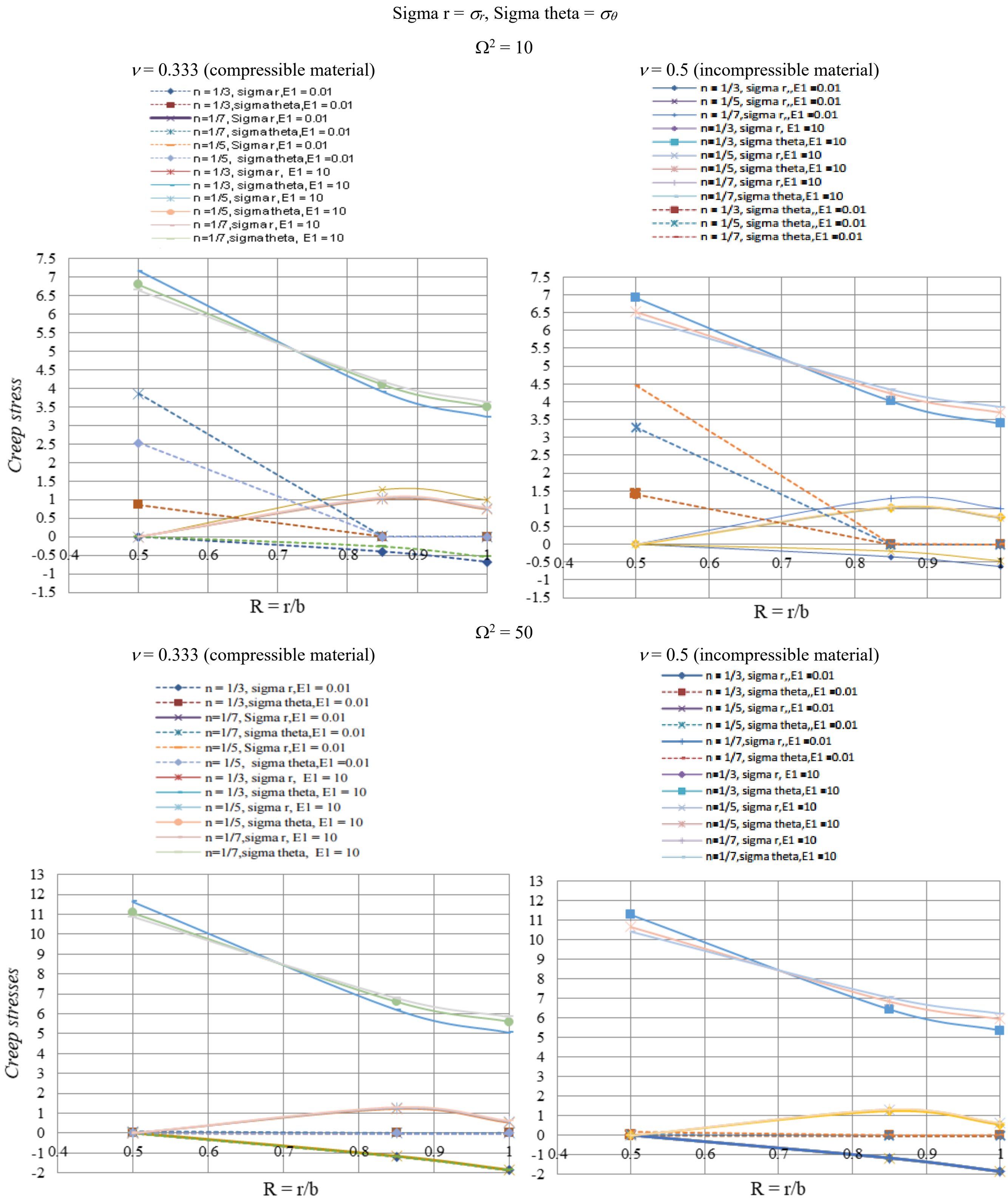


Figure 1. Creep stresses in a thin rotating disc without thickness ($k = 0$) and angular speed $\Omega^2 = 10, 50$ along the radius ($R = r/b$).

As seen from Figs. 2-3, that for a rotating disc of incompressible material whose thickness increases radially (k = 0.5, 0.7) and E_1 = 10, the circumferential stress is maximal at the internal surface for measure n = 1/7 (or N = 7) in comparison to a disc of compressible material, and this value of circumferential stress decreases as the measure decreases. For E_1 = 10, the circumferential stress has much higher values at the internal surface in comparison to E_1 = 0.01.

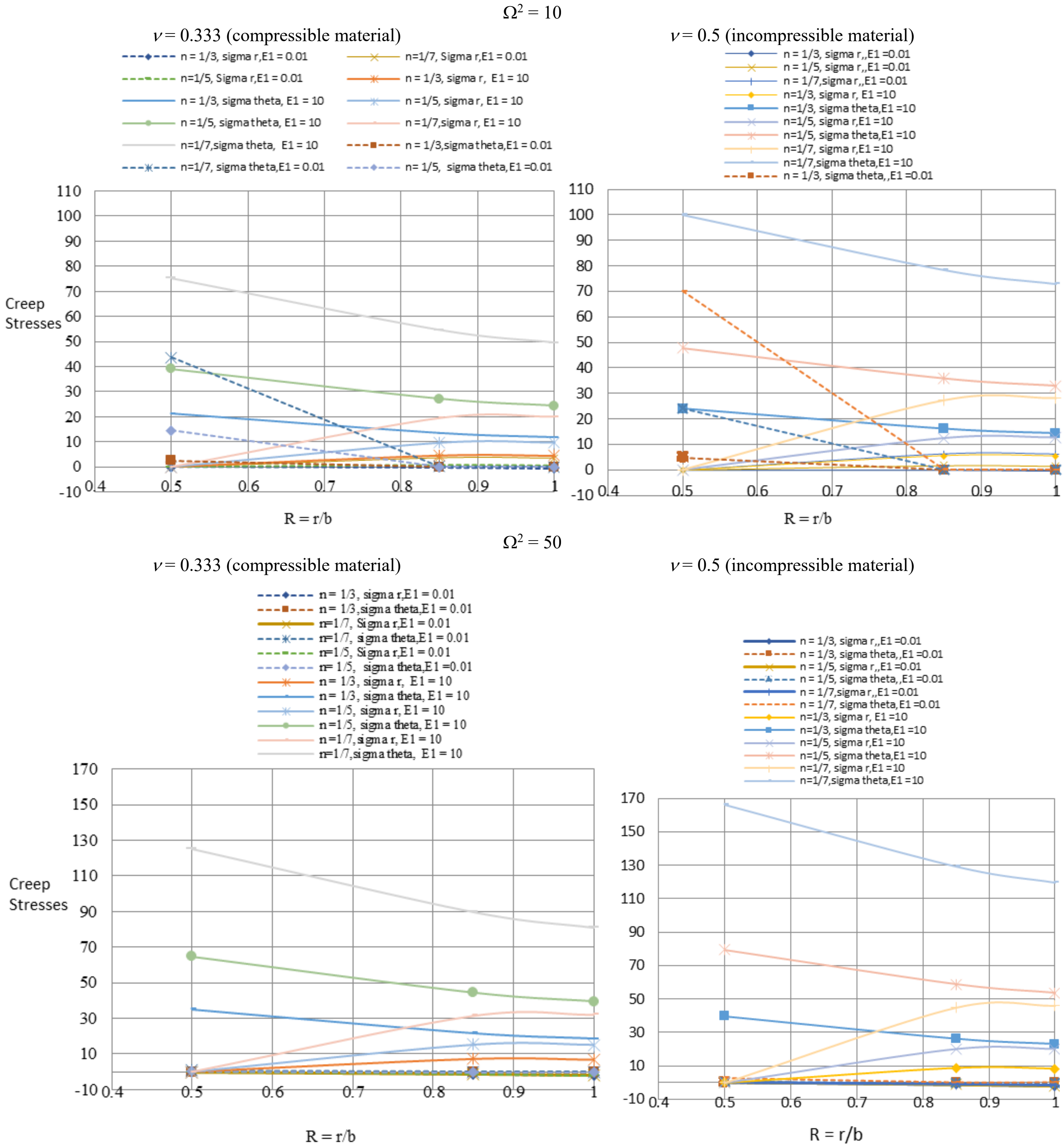
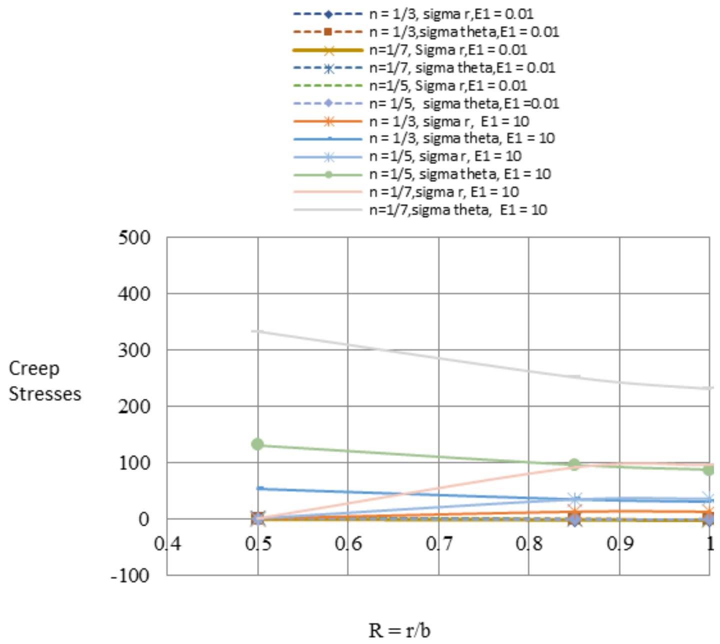


Figure 2. Creep stresses in a thin rotating disc of thickness (k = 0.5) and angular speed Ω^2 = 10, 50 along the radius (R = r/b).

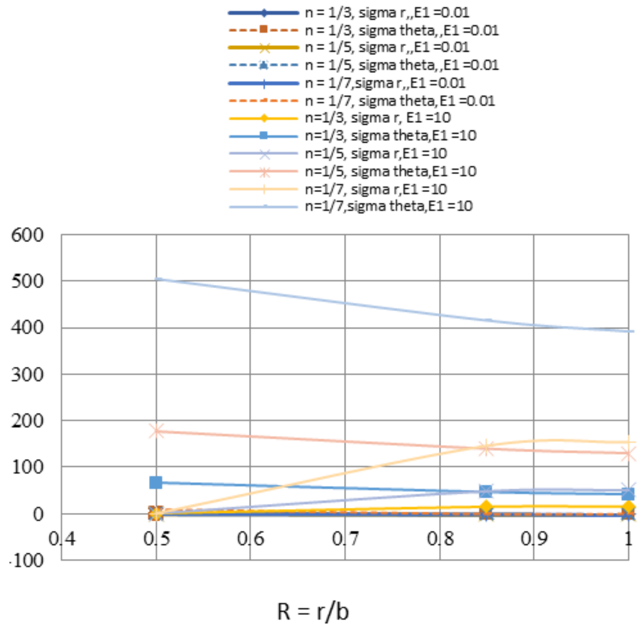
Curves are plotted for strain rates along the radii ratio R = r/b (see Fig. 4) for rotating disc of compressible material (i.e. copper) as well as incompressible material (i.e. rubber) with thickness k = 0, 0.25 at angular speed Ω^2 = 10 for measure n = 1/7, 1/5, 1/3 (i.e. N = 7, 5, 3). It has been seen that the rotating disc of incompressible material has a maximal value of strain at the internal surface as compared to the disc of compressible material for measure n = 1/7 and n = 1/5, respectively.

$\Omega^2 = 10$

$\nu = 0.333$ (compressible material)

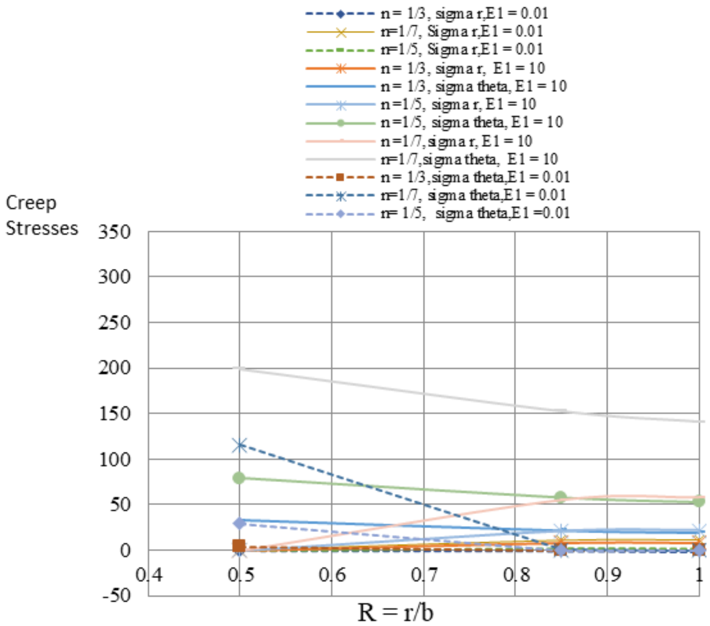


$\nu = 0.5$ (incompressible material)



$\Omega^2 = 50$

$\nu = 0.333$ (compressible material)



$\nu = 0.5$ (incompressible material)

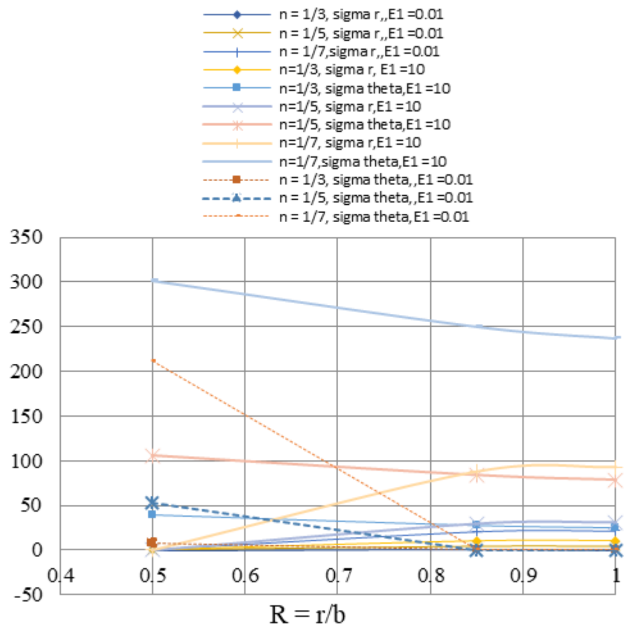


Figure 3. Creep stresses in a thin rotating disc of thickness (k = 0.7) and angular speed Ω^2 = 10, 50 along the radius ($R = r/b$).

$$\text{Err} = \dot{\varepsilon}_r\,,\ \text{Eqq} = \dot{\varepsilon}_{\theta\theta}\,,\ \text{Ezz} = \dot{\varepsilon}_{zz}$$

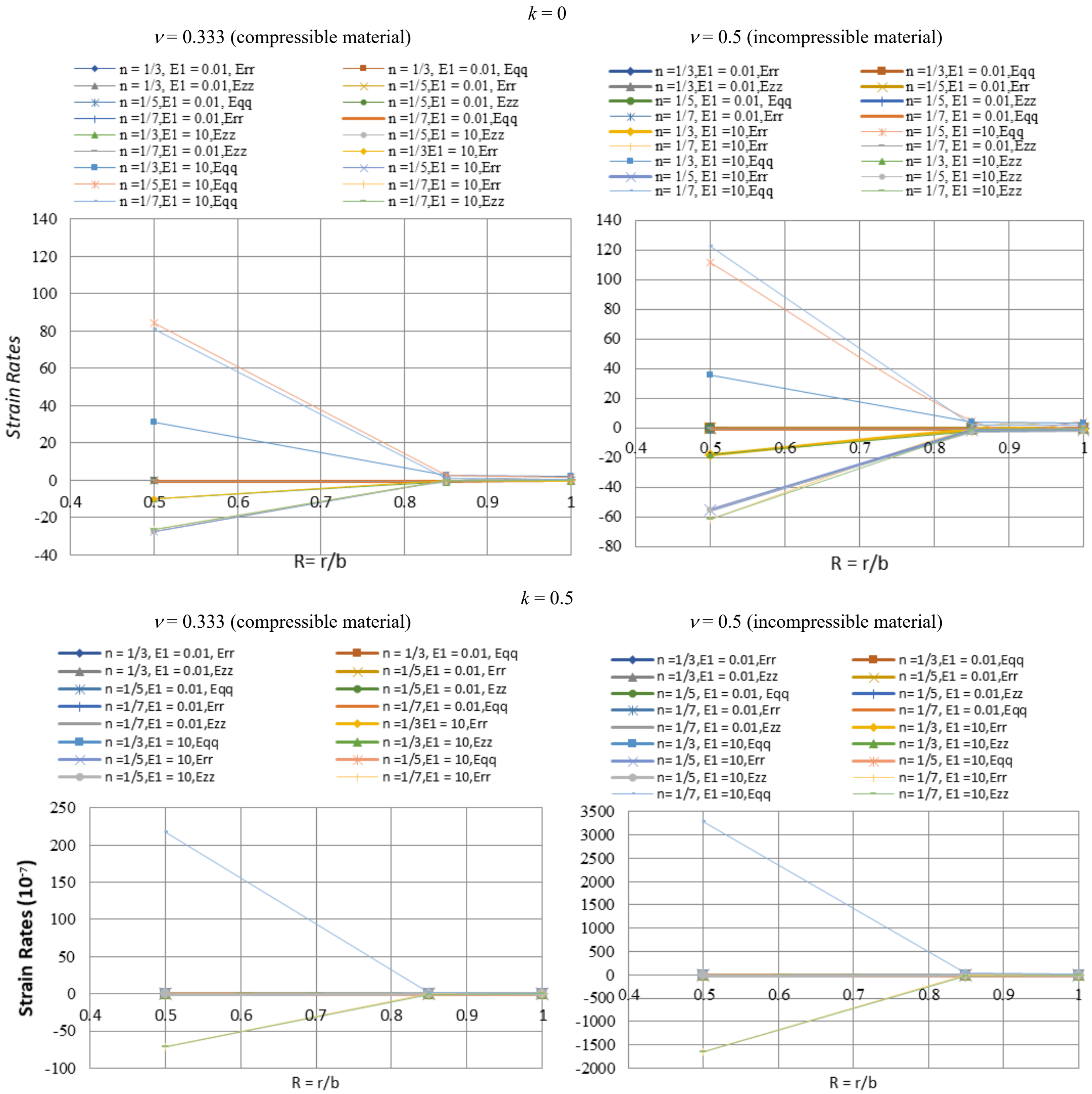


Figure 4. Creep strain rate distribution in a thin disc of variable thickness k = 0, 0.5 and angular speed Ω^2 = 10 for measure n = 1/7, 1/5, 1/3 along the radius $R = r/b$.

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