Sanjeev Sharma[1], Sanehlata Yadav[1], Zoran Radaković[2]

FINITE CREEP DEFORMATION IN THICK-WALLED CIRCULAR CYLINDER WITH VARYING COMPRESSIBILITY UNDER EXTERNAL PRESSURE

KONAČNA DEFORMACIJA PUZANJA DEBELOZIDOG KRUŽNOG CILINDRA PROMENLJIVE STIŠLJIVOSTI POD SPOLJNIM PRITISKOM

Originalni naučni rad / Original scientific paper
UDK /UDC: 539.376
Rad primljen / Paper received: 12.10.2017

Adresa autora / Author's address:
[1)] Department of Mathematics, Jaypee Institute of Information Technology, Noida, INDIA email: sanjiit12@rediffmail.com
[2)] University of Belgrade, Faculty of Mechanical Engineering, Belgrade, Serbia

Keywords
- creep
- cylinder
- pressure
- non-homogeneous
- thermal

Ključne reči
- puzanje
- cilindar
- pritisak
- nehomogenost
- termički

Abstract

Creep stresses have been obtained for thick-walled circular cylinder of compressibility varying radially under external pressure with the help of transition theory using the concept of generalized principal strain measure. This theory simplifies the constitutive equations by prescribing a priory the order of the measure of deformation. Results have been analysed and discussed numerically as well as graphically. From the numerical results, it has been observed that homogeneous material is on the safer side of the design and also highly compressible cylinder made of either homogeneous or non-homogeneous material is also on the safer side of the design.

Izvod

Izračunati su naponi puzanja u debelozidom kružnom cilindru radijalno promenljive stišljivosti, izloženom spoljnom pritisku, primenom teorije prelaznih napona, zasnovane na konceptu generalisane mere glavne deformacije. Ova teorija pojednostavljuje konstitutivne jednačine tako što a priori definiše red veličine mere deformacije. Rezultati su analizirani i razmatrani numerički i grafički. Na osnovu numeričkih rezultata je uočeno da je homogeni materijal na strani sigurnosti, kao i da je izrazito stišljiv cilindar na strani sigurnosti, bez obzira da li je homogen ili nehomogen.

INTRODUCTION

Thick-walled cylinders are widely used in chemical, petroleum, military industries as well as in nuclear power plants. They are usually subjected to high pressures and temperatures which may be constant or cycling. Creep analysis of thick-walled cylinders is an active topic, which attracts a lot of research attention. Cylinders play an important role in mechanical engineering problems. Some degree of non-homogeneity is present in wide class of materials such as hot rolled metals, aluminium and magnesium alloys. Also, this non-homogeneity can be generated by certain external fields, i.e. by thermal field, as the elastic modules of the material vary with temperature or co-ordinates etc. (Sokolinokoff, /1/; Lubahn and Felger, /2/; Odquist, /3/; Boyle and Spence, /4/). Rimrott /5/ has used assumptions of constant density, zero axial strain and distortion energy law and derived equation for creep rates, strains and stresses of a thick-walled, closed end, circular hollow cylinder made of an isotropic homogeneous material under internal pressure. The strains are considered large, and the finite strain theory has been used. A known creep rate versus stress relation is then used to solve a specific problem. Rimrott and Luke /6/ have presented creep analysis of rotating isotropic cylinder considering finite strain theory. The appropriate solution has been obtained for large strain. Creep analysis of thick-walled orthotropic cylinder made of isotropic monolithic material and subjected to internal pressure has been presented by Weir /7/; King and Mackie /8/, and in all these analyses, it was assumed that the strains are infinitesimal and the deformation is referred with respect to original dimensions of the cylinder. Assuming the plain strain condition, Bhatnagar et al. /9/ obtained stresses for an internally pressurized, homogeneous, orthotropic rotating cylinder subjected to steady state creep condition. Sharma and Yadav /10/ investigated plastic stresses using finite difference method. All these authors used the assumptions of incompressibility, yield condition, jump continuity. Seth /11, 12/, has defined that transition theory does not require these assumptions which have been applied by many authors, i.e. Gupta et. al. /13/ derived creep stresses in transversely isotropic rotating hollow and solid circular cylinders under internal pressure. Gupta and Sharma /14/ have obtained thermo creep stresses and strains in a pressurized non-homogeneous thick hollow cylinder under internal pressure, while Sharma /15/ obtained the thermal creep stresses, strain rate in a non-homogeneous thick-walled rotating cylinder using transition theory. Sharma et al. /16/ investigated elastic-plastic stresses for cylinder made up of transversely isotropic material using

Seth's transition theory. Also, this theory has been applied to determine thermal creep stresses in functionally graded rotating spherical shell (Sharma and Panchal, /17/).

In this paper, we present an approach of transition theory (Seth, /12/) to determine the creep stresses for non- homogeneous thick-walled cylinder under external pressure. Taking the non-homogeneity as the compressibility of the material in the cylinder as,

$$C = C_0 r^{-k}\,, \tag{1}$$

where: $a \le r \le b$; C_0 and k are constants.

Results obtained have been discussed numerically and depicted graphically.

The generalized principal strain measure (Seth, /11/) is defined as

$$e_{ii} = \int_0^{e_{ii}^A} [1-2e_{ii}^A]^{\frac{n}{2}-1} de_{ii}^A = \frac{1}{n}\left[1-(1-2e_{ii}^A)^{\frac{n}{2}}\right]. \tag{2}$$

OBJECTIVE OF THE STUDY

In order to explain the transition from elastic to creep, firstly, we need to recognize transition state as an asymptotic one and in this present study, it is our main aim to eliminate the need for yield condition, creep stress-strain laws, semi-empirical laws and jump conditions etc. The objective of this paper is to show that not only the stresses and strains may be obtained in transition and creep states but also the constitutive equation could be obtained in transition state. The general yield condition of transition is identified from the vanishing of the Jacobian of transformation. Creep transition of thick-walled cylinder is discussed to justify the complete theoretical approach.

MATHEMATICAL FORMULATION

Consider a non-homogeneous thick-walled circular cylinder of internal and external radii a and b respectively, subjected to external pressure p. The non-homogeneity in the cylinder is due to variation of compressibility C. The cylinder is taken so large that plane transverse sections remain plane during the expansion, and hence the longitudinal strain is the same for all elements at each stage of the expansion. In cylindrical polar co-ordinates the displacements are given by Gupta and Dharmani /13/, Gupta and Sharma /14/; Sharma /15/.

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

where: β is a function of $r = \sqrt{x^2+y^2}$ and d is a constant.

The generalized components of strain are (Gupta et al. /13/),

$$e_{rr} = \frac{1}{n}[1-(r\beta'+\beta)^n],\ \ e_{\theta\theta} = \frac{1}{n}[1-\beta^n]\,,$$
$$e_{zz} = \frac{1}{n}[1-(1-d)^n],\ \ e_{r\theta} = e_{\theta z} = e_{zr} = 0\,, \tag{4}$$

where: n is the measure and $\beta' = \dfrac{d\beta}{dr}$.

The stress-strain relation for isotropic material by Hooke's Law is

$$T_{ij} = \lambda\delta_{ij} I_1 + 2\mu e_{ij}\,;\ \ (i,j = 1, 2, 3), \tag{5}$$

where: $I_1 = e_{kk}$; T_{ij}, e_{ij} are stress and strain tensors, respectively; $\xi = \alpha(3\lambda + 2\mu)$; λ, μ are Lame's constants; δ_{ij} is the Kronecker delta.

Equations of equilibrium are all satisfied except

$$\frac{d}{dr}(T_{rr}) + \frac{(T_{rr}-T_{\theta\theta})}{r} = 0\,. \tag{6}$$

IDENTIFICATION OF TRANSITION POINTS

When a deformable solid is subjected to an external loading system, it has been observed that the solid first deforms elastically. If the loading is continued, plastic flow may set in, and if continued further it gives rise to time independent continuous deformation known as the creep deformation. It may be possible that a number of transition states may occur at some critical point, then the transition function will have different asymptotic values, and the point will be a multiple one, each branch of which will then correspond to a different state.

Using Eq.(5) in Eq.(6), and differentiating with respect to r, one gets a nonlinear equation in β as

$$nP\beta(P+1)^{n-1}\frac{dP}{d\beta} = r\left(\frac{\mu'}{\mu}-\frac{C'}{C}\right)\Big[\{(3-2C)-(1-C)\times$$
$$\times(1-d)^n\}\frac{1}{\beta^n}-(1-C)-(P+1)^n\Big]+C[1-(P+1)^n]+ \tag{7}$$
$$+r\,C'\left[1-\{2-(1-d)^n\}\frac{1}{\beta^n}\right]-nP[(1-C)+(P+1)^n]\,,$$

where: $P = \dfrac{r\beta'}{\beta}$; $C = \dfrac{2\mu}{\lambda+2\mu}$.

From Eq.(7) we see that the possible transition points are $P \to -1$ and $P \to \pm\infty$.

When $P \to -1$, then $\dfrac{\partial r'}{\partial r} \to 0$ and so $P \to -1$ corresponds to infinite extension. Similarly, when $P \to \pm\infty$ corresponds to infinite contraction. The strain ellipsoid reveals that both above mentioned points are transition points.

The boundary conditions are

$$T_{rr} = 0\ \text{at}\ r = a;\ \ T_{rr} = -p\ \text{at}\ r = b. \tag{8}$$

The resultant axial force in the cylinder is given by

$$L = 2\pi\int_a^b rT_{zz}dr\,. \tag{9}$$

METHOD OF APPROACH

The asymptotic solution at each transition point gives the solution for the transition state of a particular configuration of the problem. We observe that the material from elastic state can go over into creep state or plastic state or first to plastic and then to creep or vice versa under external loading system. All these final states are reached through a transition state. As only principal stresses are considered, therefore, the transition can take place either through the principal stresses T_{rr} or $T_{\theta\theta}$ becoming critical, or through $T_{rr} - T_{\theta\theta}$

becoming critical. It has been shown that /13-19/ transition through $T_{rr} - T_{\theta\theta}$ leads to the creep state for the critical point $P \to -1$. Then transition function R is defined as

$$R = T_{rr} - T_{\theta\theta} = \frac{2\mu\beta^n}{n}\left[1-(P+1)^n\right]. \quad (10)$$

Taking logarithmic differentiation of the Eq.(10) with respect to r and taking asymptotic value of β as $P \to -1$ and integrating, one gets

$$R = A\frac{\mu^2}{Cr^{2n}}\exp f \ , \quad (11)$$

where: A is constant of integration.

From Eqs.(10) and (11), it is found that

$$T_{rr} - T_{\theta\theta} = ArF, \ \ F = \frac{\mu^2}{Cr^{2n+1}}\exp f \ . \quad (12)$$

Substituting the value of $T_{rr} - T_{\theta\theta}$ from Eq.(12) in Eq.(6) and integrating, we get

$$T_{rr} = B - A\int F dr \ , \quad (13)$$

where: B is a constant of integration.

Constants A and B are obtained by using the boundary conditions Eq.(8) as

$$A = \frac{p}{\int_a^b F dr}; \ \ B = \frac{p}{\int_a^b F dr}\left[\int F dr\right]_{r=b} - p \ .$$

As the non-homogeneity in the cylinder is due to variable compressibility C given by Eq.(1), the creep stresses in a non-homogeneous cylinder under external pressure have been obtained as

$$T_{rr} = -p + A_2\int_r^b F_1 dr, \ \ T_{\theta\theta} = -p + A_2\left[\int_r^b F_1 dr - rF_1\right],$$

$$T_{zz} = \left(\frac{1-C_0 r^{-k}}{2-C_0 r^{-k}}\right)\left[-2p + 2A_2\int_r^a F_1 dr - rA_2F_1\right] + \quad (14)$$

$$+\frac{\lambda C_0 r^{-k}(3-2C_0 r^{-k})}{(1-C_0 r^{-k})(2-C_0 r^{-k})}e_{zz},$$

where: $$e_{zz} = \frac{\frac{L}{2\pi} - \int_a^b \frac{r(1-C_0 r^{-k})}{2-C_0 r^{-k}}[T_{rr} + T_{\theta\theta}]dr}{\lambda\int_a^b \frac{rC_0 r^{-k}(3-2C_0 r^{-k})}{(1-C_0 r^{-k})(2-C_0 r^{-k})}dr},$$

$$F_1 = \frac{r^{k-2n-1}E^2(2-C_0 r^{-k})^2}{4C_0(3-2C_0 r^{-k})^2}\exp f_1,$$

$$A_2 = \frac{p}{\int_a^b F_1 dr}, \ \ f_1 = -\frac{(n-1)}{k}C_0 r^{-k} - \frac{2kC_0 r^{n-k}}{D^n(n-k)} +$$

$$+\frac{kC_0}{D^n}\int\frac{r^{n-k-1}(3-2C_0 r^{-k})}{1-C_0 r^{-k}}dr + \log(1-C_0 r^{-k}) \ .$$

Equation (14) gives creep stresses for a thick-walled circular cylinder having variable compressibility.

Let us now introduce the following non-dimensional components as

$$R_0 = \frac{a}{b}, \ \ R = \frac{r}{b}, \ \ \sigma_r = \frac{T_{rr}}{E}, \ \ \sigma_\theta = \frac{T_{\theta\theta}}{E}, \ \ \sigma_z = \frac{T_{zz}}{E}, \ \ \frac{p}{E} = P \ .$$

(10)

Equation (14) in non-dimensional form can be written as

$$\sigma_r = -P + P\frac{\int_R^1 F_2 dr}{\int_{R_0}^1 F_2 dr},$$

$$\sigma_\theta = -P + P\frac{\int_R^1 F_2 dr - RF_2}{\int_{R_0}^1 F_2 dr}\sigma_r \ , \quad (15)$$

$$\sigma_z = \frac{1-C_0R^{-k}b^{-k}}{2-C_0R^{-k}b^{-k}}(\sigma_\theta + \sigma_r) + e_{zz},$$

where: $$e_{zz} = \frac{\frac{L}{2\pi} - \int_{R_0}^1 Rb\frac{1-C_0R^{-k}b^{-k}}{2-C_0R^{-k}b^{-k}}(\sigma_\theta + \sigma_r)dR}{\int_R^1 2b^2 REdR};$$

$$A_2 = \frac{P}{\int_{R_0}^1 bF_2 dR};$$

$$F_2 = \frac{E^2}{4C_0}\left(\frac{2-C_0R^{-k}b^{-k}}{3-2C_0R^{-k}b^{-k}}\right)^2 b^{k-2n-1}R^{k-2n-1}\exp f_2 \ ;$$

$$f_2 = \frac{-(n-1)C_0R^{-k}b^{-k}}{k} - \frac{2kC_0R^{n-k}b^{n-k}}{D^n(n-k)} + \frac{kC_0}{D^n}\times$$

$$\times\int\frac{3-2C_0R^{-k}b^{-k}}{1-C_0R^{-k}b^{-k}}R^{n-k-1}b^{n-k}dR + \log(1-C_0R^{-k}b^{-k}).$$

STRAIN RATES

When the creep sets in, the strain should be replaced by strain rates. The stress-strain relation (5) can be written as

$$\dot{e}_{ij} = \frac{1+\nu}{E}T_{ij} - \frac{\nu}{E}\delta_{ij}\Theta \ , \quad (16)$$

where: $\dot{e}_{ij}$ is the strain rate tensor with respect to flow parameter t and $\Theta = T_{11} + T_{22} + T_{33}$ and $\nu = \frac{1-C}{2-C}$ is the Poisson ratio.

Differentiating Eq.(4) with respect to t, we get

$$\dot{e}_{\theta\theta} = -\beta^{n-1}\dot{\beta} \ . \quad (17)$$

For Swainger measure ($n = 1$)

$$\dot{\varepsilon}_{\theta\theta} = -\dot{\beta} \ , \quad (18)$$

where: $\dot{\varepsilon}_{\theta\theta}$ is Swainger strain measure.

The transition value of Eq.(10) as $P \to -1$ gives

$$\beta = \left(\frac{n}{2\,\mu}\right)^{\frac{1}{n}} (T_{rr} - T_{\theta\theta})^{\frac{1}{n}} \,. \tag{19}$$

Using Eqs.(17), (18) and (19) in Eq.(16), we have

$$\dot{\varepsilon}_{\theta\theta} = \left[\frac{n}{2\mu}(T_{rr} - T_{\theta\theta})\right]^{\frac{1}{n}-1} \left[\frac{1+\nu}{E}T_{ij} - \frac{\nu}{E}\delta_{ij}\Theta\right], \text{ i.e.}$$

$$\dot{\varepsilon}_{rr} = \left[\frac{3-2C}{N(2-C)}\right]^{N-1} (\sigma_r - \sigma_\theta)^{N-1}\left[\sigma_r - \frac{1-C}{2-C}(\sigma_z + \sigma_\theta)\right], \tag{20}$$

$$\dot{\varepsilon}_{\theta\theta} = \left[\frac{3-2C}{N(2-C)}\right]^{N-1} (\sigma_r - \sigma_\theta)^{N-1}\left[\sigma_\theta - \frac{1-C}{2-C}(\sigma_r + \sigma_z)\right], \tag{21}$$

and

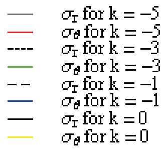
$$\dot{\varepsilon}_{zz} = \left[\frac{3-2C}{N(2-C)}\right]^{N-1} (\sigma_r - \sigma_\theta)^{N-1}\left[\sigma_z - \frac{1-C}{2-C}(\sigma_r + \sigma_\theta)\right] = -\dot{\varepsilon}_0 \,. \tag{22}$$

These are the constitutive equations for finding the creep strains for $N = 1/n$.

NUMERICAL DISCUSSION

In order to explain the effect of pressure and compressibility on cylinders made up of homogeneous and non-homogeneous materials, curves have been drawn in Figs. 1 to 3 between stresses and radii ratios $R_0 = 0.1{:}0.1{:}1$.

From Fig. 1, it is observed that circumferential stresses are compressible and maximal at the internal surface for cylinder made of homogeneous and non-homogeneous material with linear measure ($N = 1$). Also, it is observed from Fig. 1 that circumferential stresses are maximal for highly compressible cylinder as compared to the less compressible cylinder. As measure changes from linear to nonlinear ($N = 3$), circumferential stresses with compressibility parameter ($k = -5, -3$) are again maximum at the internal surface while for ($k = -1$), it becomes maximum at $R_0 = 0.6$ with external pressure ($P = 1$). As nonlinear measure increases, behaviour of circumferential stresses remains the same as that for nonlinear measure ($N = 5$). Also, with the external pressure we can observe from Fig. 2 that circumferential stresses are compressible and maximal at internal surface for cylinder made of homogeneous and non-homogeneous material with linear measure ($N = 1$). Also, as observed from Fig. 1, the circumferential stresses are maximal for highly compressible cylinder as compared to less compressible cylinder. As measure changes from linear to nonlinear ($N = 3$), circumferential stresses with compressibility parameter ($k = -5, -3$) are again maximal at internal surface while for ($k = -1$), it becomes maximal at $R_0 = 0.6$ with external pressure ($P = 2$). As nonlinear measure increases, the behaviour of circumferential stresses remains the same as that for nonlinear measure ($N = 5$). We can see that for linear/nonlinear measure, circumferential stresses increase significantly but the behaviour of stresses remains the same as in Fig. 1. Similarly, from Fig. 3, it is observed that circumferential stresses are compressible and maximal at the internal surface of cylinder made of homogeneous and non-homogeneous material with linear measure ($N = 1$). Also, it is observed from Fig. 1 that circumferential stresses are maximal for highly compressible cylinder as compared to the less compressible cylinder. As measure changes from linear to nonlinear ($N = 3$), circumferential stresses with compressibility parameter ($k = -5, -3$) are again maximum at the internal surface while for ($k = -1$), it becomes maximal at $R_0 = 0.6$ with external pressure ($P = 2$). As nonlinear measure increases, the behaviour of circumferential stresses remains the same as that for non-linear measure ($N = 5$). We can see form the figure that as pressure changes, $P = 2$ to $P = 3$, circumferential stresses increase significantly for both linear and nonlinear measure, but the behaviour of stresses remains the same as in Figs. 1 and 2.



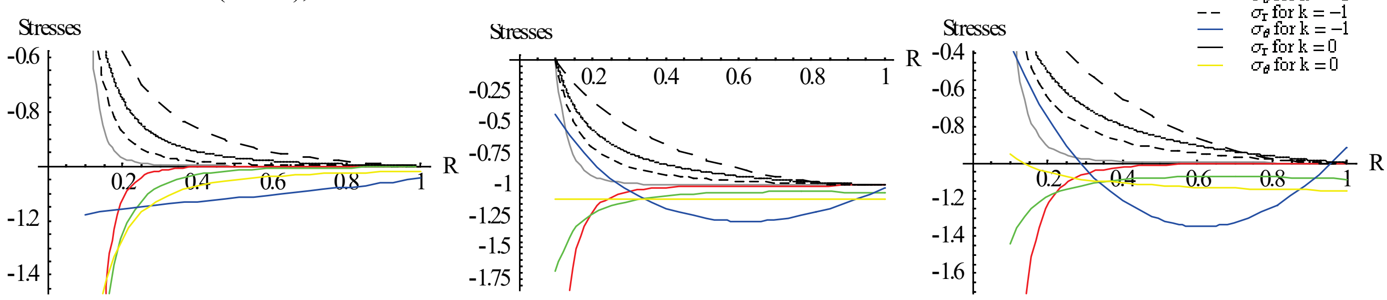


Figure 1. Creep stresses in thick-walled circular cylinder under external pressure ($p = 1$) for measure $N = 1, 3, 5$ in respect.

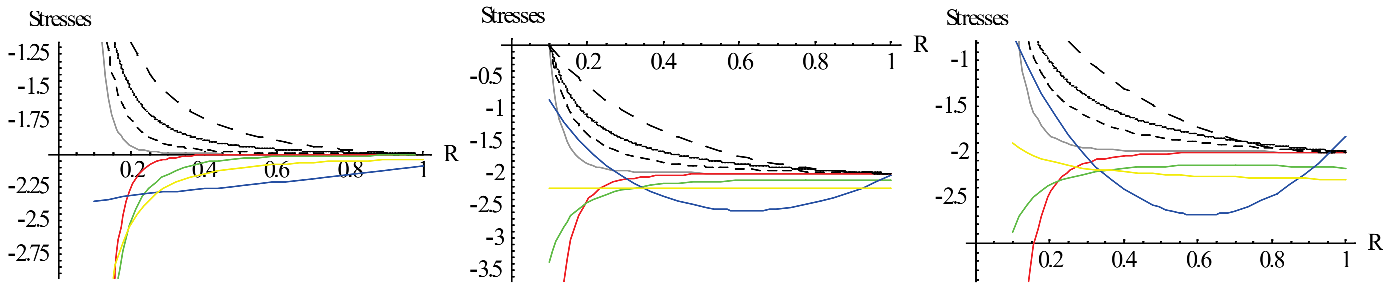


Figure 2. Creep stresses in thick-walled circular cylinder under external pressure ($p = 2$) for measure $N = 1, 3, 5$ in respect.

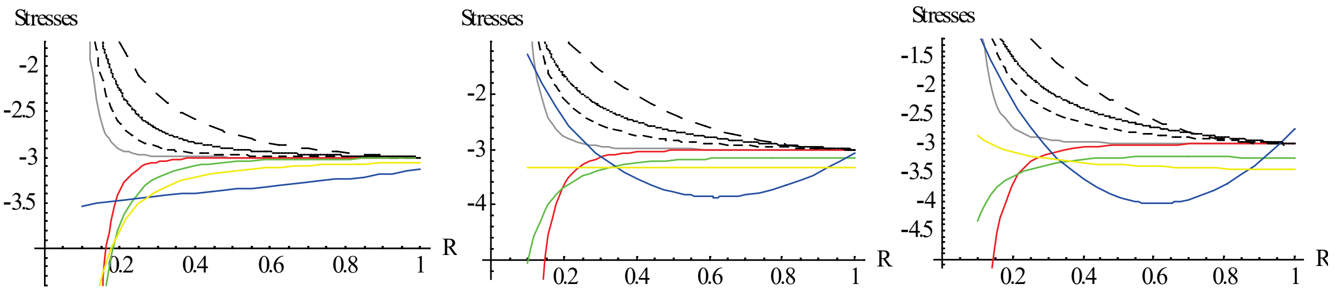


Figure 3. Creep stresses in thick-walled circular cylinder under external pressure (p = 3) for measure N = 1, 3, 5 in respect.

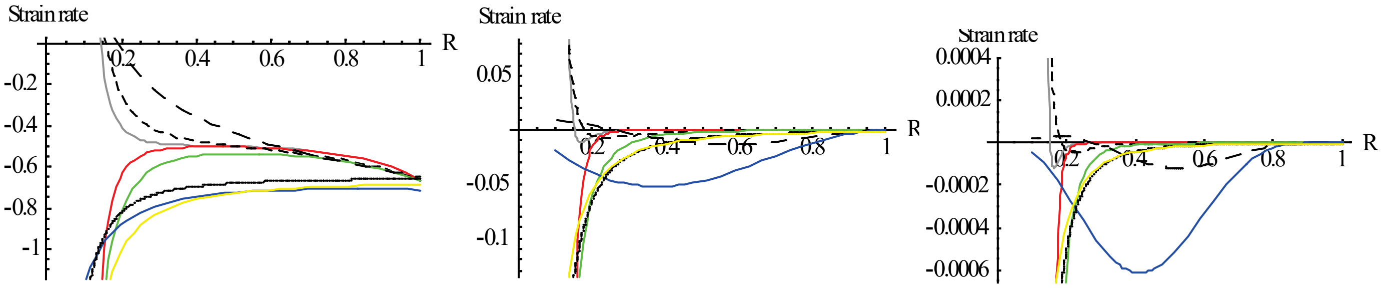


Figure 4. Creep strain rates in homogeneous thick-walled circular cylinder under external pressure (p = 1) for measure N = 1, 3, 5 in respect.

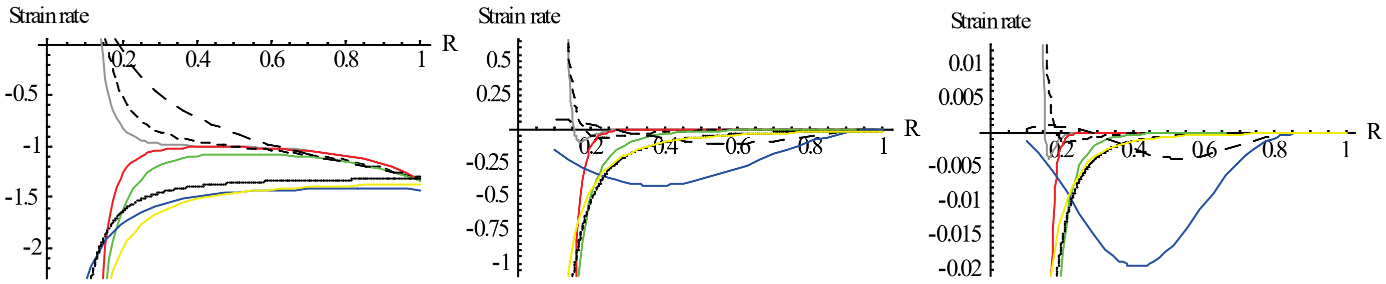


Figure 5. Creep strain rates in thick-walled circular cylinder under external pressure (p = 2) for measure N = 1, 3, 5 in respect.

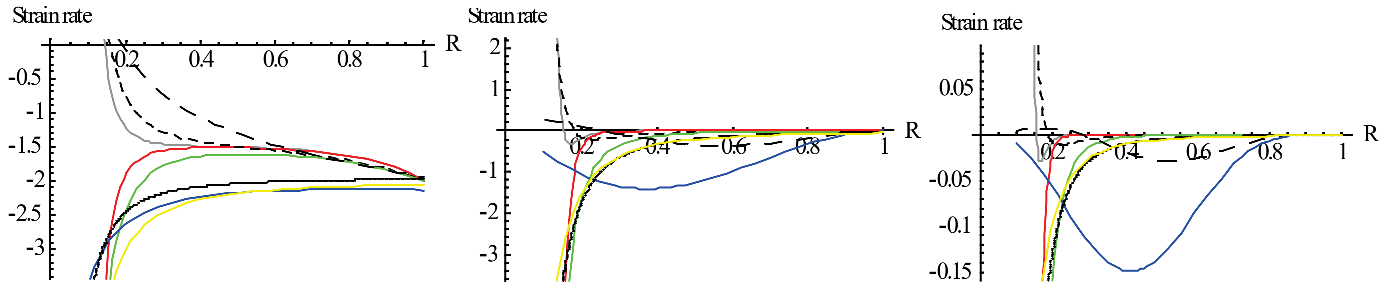


Figure 6. Creep strain rates in thick-walled circular cylinder under external pressure (p = 3) for measure N = 1, 3, 5 in respect.

From Fig. 4, we can observe that creep strain rates are maximal at internal surface for homogeneous cylinder and non-homogeneous cylinder with linear measure. From Fig. 4, we can see that as measure changes from linear to nonlinear, creep strain rates decrease significantly for non-homogeneous cylinder as well as for the homogeneous cylinder. It can be observed from Figs. 4 and 5 that when external pressure changes from P = 1 to P = 2, creep strain rates increase significantly but as measure changes from linear to nonlinear, creep strain rates keep going on decreasing. Similarly, we can see from Figs. 5 and 6 that as pressure increases, creep strain rates increase significantly.

CONCLUSION

From the above analysis above we can conclude that circumferential stresses are lower for non-homogeneous cylinder with compressibility parameter ($k = -1$) under external pressure as compared to the homogeneous cylinder and non-homogeneous cylinder with other compressibility parameters. Thus, non-homogeneous cylinder with linear measure is a better choice for the design as compared to the homogeneous cylinder and non-homogeneous cylinder with nonlinear measure.

REFERENCES

1. Sokolinokoff, I.S. (1956) Mathematical Theory of Elasticity, 2nd Ed., McGraw-Hill, New York.
2. Lubahn, D., Felger, R.P. (1961) Plasticity and Creep of Metals, Wiley, New York.
3. Odquist, F.K.G. (1974) Mathematical Theory of Creep and Creep Rupture, Clarendon Press, Oxford, UK.
4. Boyle, J.T., Spence, J. (1983) Stress Analysis for Creep, Butterworths Company Ltd., Boston.

5. Rimrott, F.P.J. (1959) *Creep of thick-walled tube under internal pressure considering large strains,* J Appl. Mech., Trans. ASME, 26: 271-274.
6. Rimrott, F.P.J., Luke, J.R. (1961) *Large strain creep of rotating cylinder*, ZAMM, 41: 485-500.
7. Weir, C.D. (1957) *The creep of thick-walled cylinder under internal pressure*, J Appl. Mech. (Trans. of ASME), 79: 464-466.
8. King, R.H., Mackie, W.W. (1969) *Creep of thick-walled cylinders*, Jr. Basic Engrs., 87: 877-879.
9. Gupta, S.K., Bhatnagar, N.S. (1977), *Creep of orthotropic thick-walled cylinder under combined axial load and internal pressure,* J Aero. Soc. of India, 29(3-4): 141-144.
10. Sharma, S., Yadav, S., (2013), *Thermo elastic-plastic analysis of rotating functionally graded stainless steel composite cylinder under internal and external pressure using finite difference method*, Advanc. in Mater. Sci. and Eng., 2013, http://dx.doi.org/10.1155/2013/ 810508.
11. Seth, B.R. (1966) *Measure concept in mechanics,* Int. J Non-linear Mech., 1(1): 35-40.
12. Seth, B.R. (1972) *Creep transition in cylinders,* Courses and Lecture No.149, Inter. Centre Mech. Sci., Udine, Italy.
13. Gupta, S.K., Dharmani, R.L. (1979) *Creep transition in thick-walled cylinder under internal pressure,* ZAMM, 59: 517-521.
14. Gupta, S.K., Sharma, S. (1998) *Thermo creep transition of non-homogeneous thick-walled circular cylinder under internal pressure,* Ind. J Pure & Appl. Math., 29(11): 1111-1125.
15. Sharma, S. (2009), *Thermo creep transition in non-homogeneous thick-walled rotating cylinders,* Defence Sci. J, 59(1): 30-36.
16. Sharma, S., Sahai, I., Kumar, R. (2014), *Thermo elastic-plastic transition of transversely isotropic thick-walled circular cylinder under internal and external pressure*, Multidis. Model. in Mater. and Struc., 10(2): 211-227.
17. Sharma, S., Panchal, R. (2017), *Thermal creep deformation in pressurized thick-walled functionally graded rotating spherical shell*, Int. J Pure and Appl. Math., 114(3): 435-444.
18. Sharma, S. (2017), *Stress analysis of elastic-plastic thick-walled cylindrical pressure vessels subjected to temperature*, Struc. Integ. and Life, 17(2): 105-112.
19. Sharma, S. (2017), *Creep transition in bending of functionally graded transversely isotropic rectangular plates*, Struc. Integ. and Life, 17(3): 187-192.