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THERMAL CREEP ANALYSIS IN NON-HOMOGENEOUS SPHERICAL SHELL

ANALIZA PUZANJA U NEHOMOGENOJ SFERNOJ LJUSCI

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Keywords
- strain rates
- thermal
- spherical shell
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- stress

Abstract

The purpose of this paper is to present study of thermal creep stress and strain rates in non-homogeneous spherical shell by using Seth's transition theory. Seth's transition theory is applied to the problem of creep stresses and strain rates in non-homogeneous spherical shell under steady-state temperature. Neither the yield criterion nor the associated flow rule is assumed here. With the introduction of thermal effect, the values of circumferential stress decrease at the external surface as well as at the internal surface of the spherical shell for different values of non-homogeneity. It means that the temperature dependent materials minimize the possibility of a fracture at the internal surface of the spherical shell. The model proposed in this paper is used commonly in the design of chemical and oil plants, industrial gas and steam turbines, high speed structures involving aerodynamic heating.

Ključne reči
- brzina deformacije
- toplota
- sferna ljuska
- nehomogeni
- naponi

Izvod

Cilj ovog rada je prikaz istraživanja napona i brzine deformacija usled puzanja kod nehomogene sferne ljuske primenom teorije Seta. Teorija Seta je primenjena na problem rešavanja napona i brzina puzanja kod nehomogene sferne ljuske u stacionarnim uslovima raspodele temperature. Ovde se ne pretpostavlja niti kriterijum tečenja ni odgovarajući zakon toka plastičnosti. Uvođenjem toplotnog efekta, vrednosti obimnih napona opadaju na spoljnoj površini, kao i na unutrašnjoj površini sferne ljuske, za različite vrednosti nehomogenosti. Zapravo, u materijalima koji poseduju temperatursku zavisnost se smanjuje verovatnoća pojave loma na unutrašnjoj površini ljuske. Predstavljeni model se često koristi u postrojenjima hemijske i naftne industrije, u gasnim i parnim turbinama, u konstrukcijama namenjenim velikim brzinama sa aerodinamičkim zagrevanjem.

INTRODUCTION

Spherical shell structures have found widespread use in modern technology such as design of chemical and oil plants, accumulator shells, pressure vessel for industrial gases, or a media transport of high-pressurized fluids and piping of nuclear containment, high speed structures involving aerodynamic heating, submerged undersea structures, earth sheltered domes, and the like. These spherical systems are effective from the perspectives of both structural and architectural design. In many of these cases, the spherical shells have to operate under severe mechanical and thermal loads, causing significant creep and thus reducing service life. The collapse or damage is initiated by creep, shrinkage and thermal effects, or from their interaction, on structures that both- experience or do not experience environmental degradation. Consequently, a demand for strengthening and upgrading existing concrete structures, because of damage caused by long-term effects and excessive structural deformations, has been recognized. However, before the application of costly strengthening techniques, an understanding of the nonlinear long-term behaviour of existing and new spherical shells is essential and the development of suitable and reliable theoretical approaches for their analysis and safety assessment is required. Creep effects generally increase deformations in a shell structure even under room temperature, and are usually only considered to affect behaviour at the service ability limit states. Therefore, the analysis of long term steady state creep deformation of shells is very important in these applications /1, 2/. Due to occurrence of these creep deformations, non-homogeneous materials are widely use in engineering applications. Non-homogeneous materials are the specific class of composite materials known as functionally graded materials (FGM) in which the constituents are graded in one or more direction with continuous variation to achieve the desired properties. The smooth grading of constituents result in better thermal properties, higher fracture toughness, improved residual stress distribution and the reduced stress intensity factors. These properties allow non-homogeneous structures to withstand high pressure under elevated thermal environment. Therefore, the analysis of non-homogeneity in the spherical shell through the mathematical model by taking one and all the complexities into the consideration are the major concern of the researchers /3/. Some degree of non-homogeneity is present in the wide class of materials such as hot rolled metals, magnesium and aluminium alloys. Non-homogeneity can also be introduced by certain external fields, e.g. thermal gradient materials, as the elastic modules of the material vary with temperature, /4/. Penny /5/ obtained the effects of creep in spherical shells by an analysis similar to the corresponding elastic one. Miller /6/ evaluated solutions for stresses and displacements in a thick spherical shell subjected to internal and external pressure loads. You *et. al*. /7/ presented an accurate model to carry out elastic analysis of thick-walled spherical pressure vessels subjected to internal pressure. Kellogg *et. al*. /8/ developed a finite element model of convection in a spherical, axisymmetric shell that we use to simulate upwelling thermal plumes in the mantle. Thakur /9/ has analysed creep transition stresses of a thick isotropic spherical shell by finitesimal deformation under steady state of temperature and internal pressure by using Seth transition theory. Seth's transition theory does not acquire any assumptions as in a yield condition, incompressibility condition and thus poses and solves a more general problem from which cases pertaining to the above assumptions can be worked out. This theory utilizes the concept of generalized strain measure and asymptotic solution at critical points or turning points of the differential equations defining the deformed field and is successfully applied to a large number of problems, /9-14/. Seth /11/ has defined the concept of generalized strain measures as

$$e_{ii}=\int_0^{\overset{A}{e}_{ii}}\left[1-2\overset{A}{e}_{ii}\right]^{\frac{n}{2}-1}d\overset{A}{e}_{ii}=\frac{1}{n}\left[1-\left(1-2\overset{A}{e}_{ii}\right)\right],\ i=1,2,3 \tag{1}$$

where n is the measure, and $\overset{A}{e}_{ii}$ are the Almansi finite strain components. For n = –2, –1, 0, 1, 2 it gives Cauchy, Green Hencky, Swainger and Almansi measures respectively. Non-homogeneity in a spherical shell is taken such as the compressibility of the material as

$$C=C_0 r^{-k} \tag{2}$$

where $a \le r \le b$, C_0 and k are real positive constants.

MATHEMATICAL MODEL AND GOVERNING EQUATIONS

We consider a spherical shell, whose internal and external radii are a and b respectively, subjected to uniform internal pressure p of gradually increasing magnitude and a temperature Θ_0 applied to the internal surface $r = a$ of the spherical shell as shown in Fig. 1. The components of displacement in spherical polar co-ordinates are given /10, 11/:

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

where u, v, w (displacement components); β is the position function, depending on r.

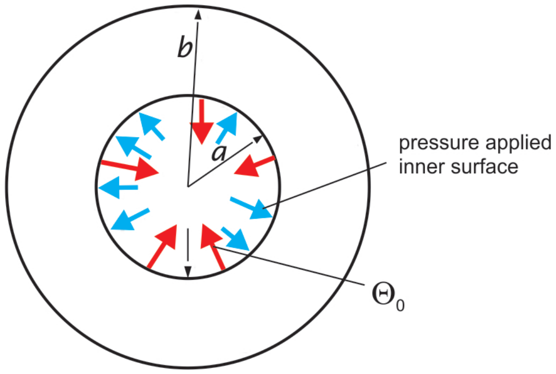


Figure 1. Geometry of spherical shell.

The generalized components of strain are given by Seth, /11/:

$$\begin{aligned} e_{rr}&=\frac{1}{n}\left[1-(r\beta'+\beta)^n\right]\\ e_{\theta\theta}&=\frac{1}{n}\left[1-\beta^n\right]=e_{\phi\phi}\\ e_{r\theta}&=e_{\theta z}=e_{zr}=0\end{aligned} \tag{4}$$

where n is measure and $\beta' = d\beta/dr$.

Stress-strain relation: the stress-strain relations for thermo-elastic isotropic material are given by /15/:

$$T_{ij}=\lambda\delta_{ij}I_1+2\mu e_{ij}-\xi\Theta\delta_{ij}\ ,\ i,j=1,2,3 \tag{5}$$

where T_{ij} are the stress components; λ and μ are Lame's constants; $I_1 = e_{kk}$ is the first strain invariant; δ_{ij} is the Kronecker's delta; and $\xi = \alpha(3\lambda + 2\mu)$; α being the coefficient of thermal expansion; and Θ is temperature. Further, Θ has to satisfy:

$$\nabla^2\Theta = 0 \tag{6}$$

Substituting the strain components from Eq.(4) into Eq.(5), the stresses are obtained as:

$$\begin{aligned} T_{rr}&=\frac{2\mu}{n}\left[1-(r\beta'+\beta)^n\right]+\frac{\lambda}{n}\left[3-(r\beta'+\beta)^n-2\beta^n\right]-\xi\Theta\\ T_{\theta\theta}&=T_{\phi\phi}=\frac{2\mu}{n}\left[1-\beta^n\right]+\frac{\lambda}{n}\left[3-(r\beta'+\beta)^n-2\beta^n\right]-\xi\Theta\\ T_{r\theta}&=T_{\theta\phi}=T_{\phi r}=0\end{aligned} \tag{7}$$

Equation of equilibrium: the radial equilibrium of an element of spherical shell requires:

$$\frac{dT_{rr}}{dr}+\frac{2}{r}(T_{rr}-T_{\theta\theta})=0 \tag{8}$$

where T_{rr} and $T_{\theta\theta}$ are the radial and hoop stresses, respectively.

Boundary conditions: the temperature satisfying Laplace Eq.(6) with boundary condition:

$$\begin{aligned}&\Theta=\Theta_0 \text{ and } T_{rr}=-p_i \text{ at } r=a\\ &\Theta=0 \text{ and } T_{rr}=0 \text{ at } r=b,\end{aligned} \tag{9}$$

where Θ_0 is constant, given by /15/:

$$\Theta=\frac{\Theta_0\ln(r/b)}{\ln(a/b)} \tag{10}$$

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

$$nP(P+1)^{n-1}\beta^{n+1}\frac{dP}{d\beta}=r\left(\frac{\mu'}{\mu}-\frac{C'}{C}\right)\Big[(3-2C)-$$
$$-\beta^n\left\{2(1-C)+(1+P)^n\right\}\Big]-2C'r(1-\beta^n)-n\beta^nP\times$$
$$\times\left\{2(1-C)+(1+P)^n\right\}+2C\beta^n\left[1-(1+P)^n\right]- \quad (11)$$
$$-\frac{nc\bar{\Theta}_0}{2\mu\beta^n}\left[\xi+r\xi'\log\frac{r}{b}\right]$$

where $\bar{\Theta}_0=\Theta_0/\log(a/b)$, $C=2\mu/\lambda+2\mu$ and $r\beta=\beta P$ (P is the function of β, and β is a function of r only). The transition points or turning point of β in Eq.(11) are $P\to-1$ and $P\to\pm\infty$.

FORMULATION AND ANALYTICAL SOLUTION

For finding the thermal creep stresses and strain rates, the transition function is taken through principal stress difference /9-14/ at the transition point $P\to-1$. We define the transition function Ψ as:

$$\Psi=T_{rr}-T_{\theta\theta}=\frac{2\mu\beta^n}{n}\left[1-(P+1)^n\right] \quad (12)$$

where Ψ is a function of r only and Ψ is the dimension.

Taking the logarithmic differentiation of Eq.(12) with respect to r and substituting the value of $dP/d\beta$ from Eq.(11), we get:

$$\frac{d}{dr}(\log\Psi)=\frac{np}{r}+\frac{\mu'}{\mu}-\left[r\left(\frac{\mu'}{\mu}-\frac{C'}{C}\right)\Big[(3-2C)-\beta^n\cdot\right.$$
$$\cdot\left\{2(1-C)+(1+P)^n\right\}\Big]-2rC'(1-\beta^n)-n\beta^nP\cdot$$
$$\cdot\left[2(1-C)+(1+P)^n\right]+2C\beta^n\left\{1-(1+P)^n\right\}-\frac{nc\bar{\Theta}_0}{2\mu}\cdot \quad (13)$$
$$\left.\cdot\left[\xi+r\xi'\log\frac{r}{b}\right]\right]\cdot\frac{1}{r\beta^n\left[1-\left\{(1+P)^n\right\}\right]}$$

Taking asymptotic value of Eq.(13) at $P\to-1$, we get:

$$\frac{d}{dr}\log\Psi=\frac{3\mu'}{\mu}-\frac{2C'}{C}-\frac{3n}{r}+X \quad (14)$$

where

$$X=\frac{2(n-1)C}{r}-\frac{2C\mu'}{\mu}+\frac{2C'}{\beta^n}-\left(\frac{\mu'}{\mu}-\frac{C'}{C}\right)\cdot$$
$$\cdot\frac{(3-2C)}{\beta^n}+\frac{nC\bar{\Theta}_0}{2\mu r\beta^n}\left[\xi+r\xi'\log\frac{r}{b}\right]$$

Integrating Eq.(14), we get

$$\Psi=A\frac{\mu^3}{C^2r^{3n}}\exp h \quad (15)$$

where $h=\int Xdr$, and A is constant of integration, which can be determined by the boundary condition. From Eqs.(12) and (15), we have

$$T_{rr}-T_{\theta\theta}=A\frac{2r\mu^3}{2C^2r^{3n+1}}\exp h=\frac{ArH}{2} \quad (16)$$

where

$$H=\frac{2\mu^3}{C^2r^{3n+1}}\exp h$$

Substituting Eq.(16) in Eq.(8) and integrating, we get

$$T_{rr}=B-A\int Hdr \quad (17)$$

where B is a constant of integration which can be determined by the boundary condition and asymptotic value of β, as $P\to-1$, β is D/r, D being a constant.

Using boundary condition Eq.(9) in Eq.(17), we get

$$A=-\frac{p_i}{\int_a^b Hdr},\quad B=-\frac{p_i}{\int_a^b Hdr}\left[\int Hdr\right] \quad (18)$$

Using constant of integration B in Eq.(17), we get

$$T_{rr}=A\int_r^b Hdr \quad (19)$$

Substituting Eq.(19) into Eq.(16), we get

$$T_{\theta\theta}=T_{\phi\phi}=A\left[\int_r^b Hdr-\frac{rH}{2}\right] \quad (20)$$

We introduce the non-homogeneity in spherical shell due to variable compressibility as given in Eq.(2), then Eqs.(19) and (20) become:

$$T_{rr}=A_1\int_r^b H_1dr \quad (21)$$

$$T_{\theta\theta}=T_{\phi\phi}=A_1\left[\int_r^b H_1dr-\frac{rH_1}{2}\right] \quad (22)$$

where

$$A_1=-\frac{p_i}{\int_a^b H_1dr},$$

$$H_1=\frac{2\mu^3}{C^2r^{3n+1}}\exp h_1=\frac{r^{-(3n+k+1)}C_0\lambda^3}{4\left(1-C_0r^{-k}\right)^3}\exp h_1,$$

$$h_1=-\frac{2(n-1)}{k}C_0r^{-k}-\frac{2kC_0r^{n-k}}{D^n(n-k)}+\frac{kC_0}{D^n}\cdot$$
$$\cdot\int\frac{r^{n-k-1}(3-2C_0r^{-k})}{(1-C_0r^{-k})}dr+2\log(1-C_0r^{-k})+$$
$$+\frac{\alpha n\bar{\Theta}_0}{D^n}\int(1-C_0r^{-k})\left[3+\frac{C_0r^{-k}}{1-C_0r^{-k}}-\frac{kC_0r^{-k}\log(r/b)}{1-C_0r^{-k}}\right]r^{n-1}dr$$

$$\frac{\mu'}{\mu}=\frac{C'}{C(1-C)},\quad C'=-kC_0r^{-k-1}.$$

Equations (21) and (22) give thermal creep stresses for a spherical shell of non-homogeneous material under steady-state temperature. We introduce the following non-dimensional components as: $R=r/b$, $R_0=a/b$, $\sigma_{rr}=\tau_{rr}/p_i$, $\sigma_{\theta\theta}=\tau_{\theta\theta}/p_i$ and $\alpha\Theta_0/p_i=\Theta_1$. Equations (21) and (22) in non-dimensional form become:

$$\sigma_{rr}=-\frac{\int_R^1 H_2dR}{\int_{R_0}^1 H_2dR} \quad (23)$$

$$\sigma_{\theta\theta}=\sigma_{\phi\phi}=\sigma_{rr}+\frac{RH_2}{2\int_{R_0}^{1}H_2 dR} \tag{24}$$

where

$$H_2=\frac{(bR)^{-(3n+k+1)}C_0\lambda^3}{4\left(1-C_0(bR)^{-k}\right)^3}\exp h_2,$$

$$h_2=-\frac{2(n-1)}{k}C_0(bR)^{-k}-\frac{2kC_0(bR)^{n-k}}{D^n(n-k)}+\frac{kC_0b^{n-k}}{D^n}\cdot$$
$$\cdot\int\frac{(R)^{n-k-1}(3-2C_0(bR)^{-k})}{1-C_0(bR)^{-k}}dr+2\log(1-C_0(bR)^{-k})+$$
$$+\frac{n\alpha\bar{\Theta}_0b^n}{D^n}\int(1-C_0(bR)^{-k})\left[3+\frac{C_0(bR)^{-k}}{1-C_0(bR)^{-k}}-\right.$$
$$\left.-\frac{kC_0(bR)^{-k}\log(R)}{(1-C_0(bR)^{-k})}\right]R^{n-1}dR$$

PARTICULAR CASE

In the absence of temperature gradient (i.e. Θ = 0), Eqs. (23) and (24) become

$$\sigma_{rr}=-\frac{\int_R^1 H_2^* dR}{\int_{R_0}^1 H_2^* dR} \tag{25}$$

$$\sigma_{\theta\theta}=\sigma_{\phi\phi}=\sigma_{rr}+\frac{bRH_2^*}{2\int_{R_0}^1 H_2^* dR} \tag{26}$$

where

$$H_2^*=\frac{(bR)^{-(3n+k+1)}C_0\lambda^3}{4\left(1-C_0(bR)^{-k}\right)^3}\exp h_2^*$$

$$h_2^*=-\frac{2(n-1)}{k}C_0(bR)^{-k}-\frac{2kC_0(bR)^{n-k}}{D^n(n-k)}+\frac{kC_0}{D^n}\cdot$$
$$\cdot\int\frac{(bR)^{n-k-1}(3-2C_0(bR)^{-k})}{1-C_0(bR)^{-k}}dr+2\log(1-C_0(bR)^{-k})$$

ESTIMATION OF CREEP PARAMETERS

When the creep sets in, the strains should be replaced by strain rates and the stress-strain relations, Eq.(5), become:

$$\dot{e}_{ij}=\frac{1+\nu}{E}T_{ij}-\frac{\nu}{E}\delta_{ij}T+\alpha\Theta \tag{27}$$

where $\dot{e}_{ij}$ is the strain rate tensor with respect to flow parameter t and $\nu = (1 - C)/(2 - C)$. Differentiating Eq.(4) with respect to time, t, we get:

$$\dot{e}_{\theta\theta}=-\beta^{n-1}\dot{\beta} \tag{28}$$

For SWAINGER measure (i.e. n = 1), Eq.(28) becomes:

$$\dot{\varepsilon}_{\theta\theta}=\dot{\beta} \tag{29}$$

where $\dot{\varepsilon}_{\theta\theta}$ is the SWAINGER strain measure. From Eq.(12) the transition value β is given at the transition point $P \to -1$ by:

$$\beta=(n/2\mu)^{1/n}[T_{rr}-T_{\theta\theta}]^{1/n} \tag{30}$$

Using Eqs.(28)-(30) in Eq.(27), we get

$$\dot{\varepsilon}_{rr}=m[\sigma_{rr}-\nu\sigma_{\theta\theta}+\alpha\Theta],$$
$$\dot{\varepsilon}_{\theta\theta}=m[\sigma_{\theta\theta}-\nu\sigma_{rr}+\alpha\Theta], \tag{31}$$
$$\dot{\varepsilon}_{\phi\phi}=-m\left[\nu(\sigma_{rr}+\sigma_{\theta\theta})+\alpha\Theta\right],$$

where $\dot{\varepsilon}_{rr}$, $\dot{\varepsilon}_{\theta\theta}$ and $\dot{\varepsilon}_{zz}$ are strain rates tensor, and $m=\left[n(\sigma_r-\sigma_\theta)(1+\nu)\right]^{\frac{1}{n}-1}$. These are the constitutive equations used by Odquist, /16/, for $n = 1/N$.

NUMERICAL RESULTS AND DISCUSSION

For calculating creep stresses and strain rates on the basis of above analysis, the following values have been taken, ν = 0.5 (incompressible material C_0 = 0), ν = 0.42857 (compressible material C_0 = 0.25) and 0.333 (compressible materials C_0 = 0.5), n = 1/3, 1/5, 1/7 (i.e N = 3, 5, 7), thermal expansion coefficient $\alpha = 5.0\cdot10^{-5}$ deg F^{-1} (for methyl methacrylate /17/, and $\Theta_1 = \alpha\Theta_0$ = 0.00 and 0.5, D =1. In classical theory the measure N is equal to $1/n$. The definite integrals in Eqs.(23) and (24) have been evaluated by using Simpson's 1/3rd rule.

From Figs. 2-4, curves are present between stresses along the radii ratio $R = r/b$ in the spherical shell of compressible, as well as incompressible material for k = –1, 0, 1. It is seen form Figs. 2-4 that the circumferential stresses are maximum at the external surface for n = 1/7 and k = –1, 0 for compressible material as compared to the incompressible material. From Fig. 4, the circumferential stresses are maximum at the internal surface for non-homogeneity k = 1. Non-homogeneity increases the values of circumferential stress (i.e. k = –1, 0), but reverses the result for k = 1.

With the introduction of temperature gradient, the values of circumferential stress decrease at the external surface as well as on the internal surface of the spherical shell for different values of non-homogeneity. It means that the temperature dependent materials minimize the possibility of a fracture at the internal surface of the spherical shell.

From Fig. 5, curves are produced between strain rates along the radii ratio $R = r/b$ for the spherical shell of compressible material (C = 0.25, i.e. saturated clay) for k = –1, 0, 1. It has been seen that strain rates are maximum at the external surface for k = –1, 0 and reverse in case k =1. With the introduction of the temperature gradient, strain rates decrease at the internal surface as well as at the external surface. It means that the temperature dependent materials minimize the possibility of a fracture at the internal surface of the spherical shell.

CONCLUSION

With the introduction of thermal effect, the values of circumferential stress decrease at the external surface as well as at the internal surface of the spherical shell for different values of non-homogeneity. It means that the temperature dependent materials minimize the possibility of a fracture at the internal surface of the spherical shell.

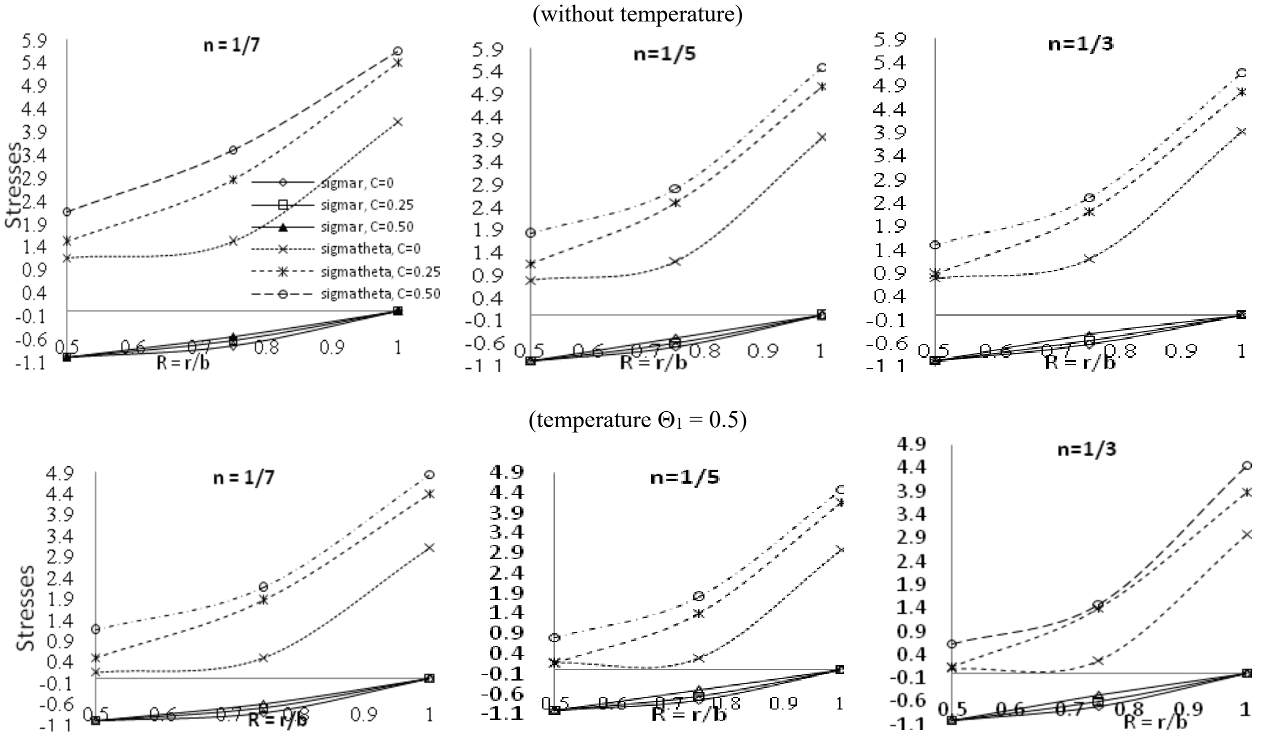


Figure 2. Creep stresses in non-homogeneous ($k = -1$) spherical shell along the radii ratio $R = r/b$.

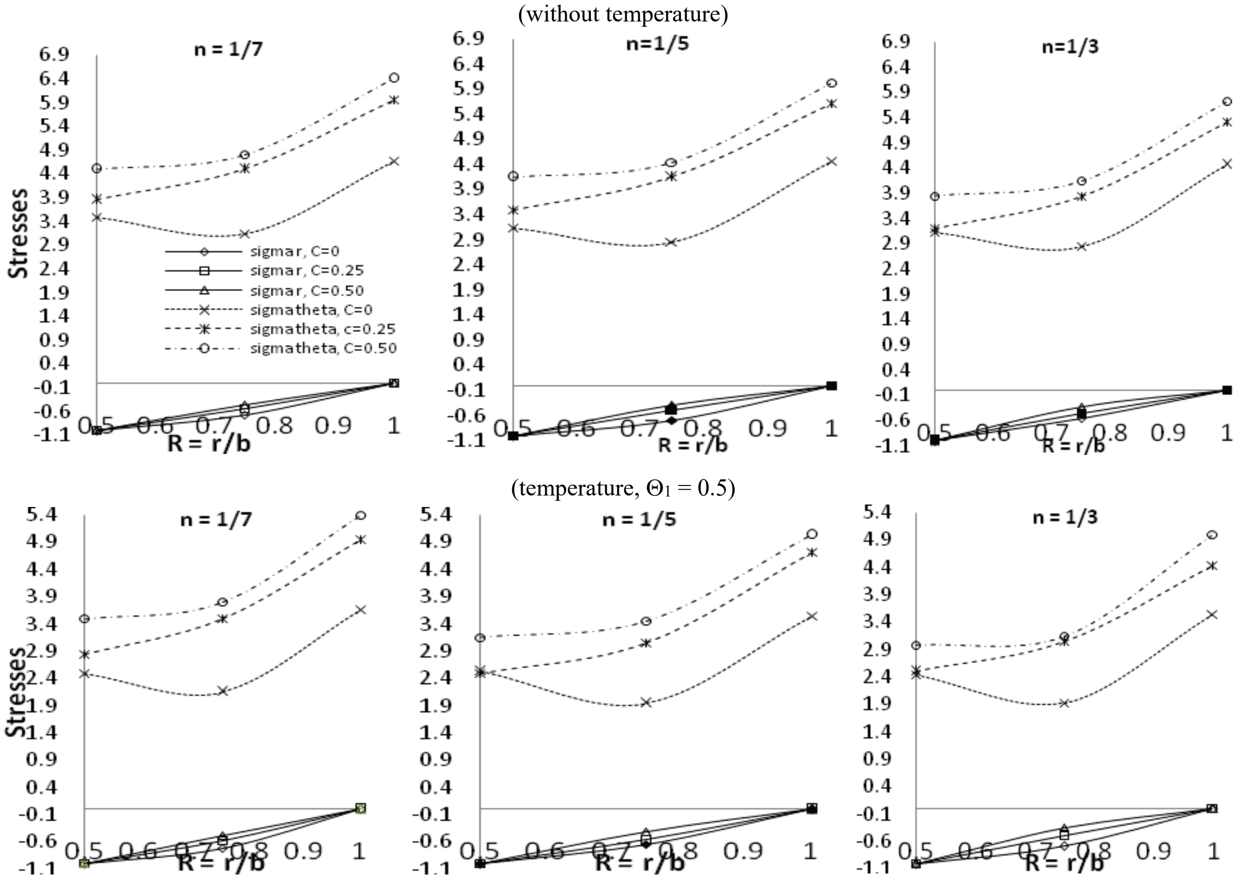
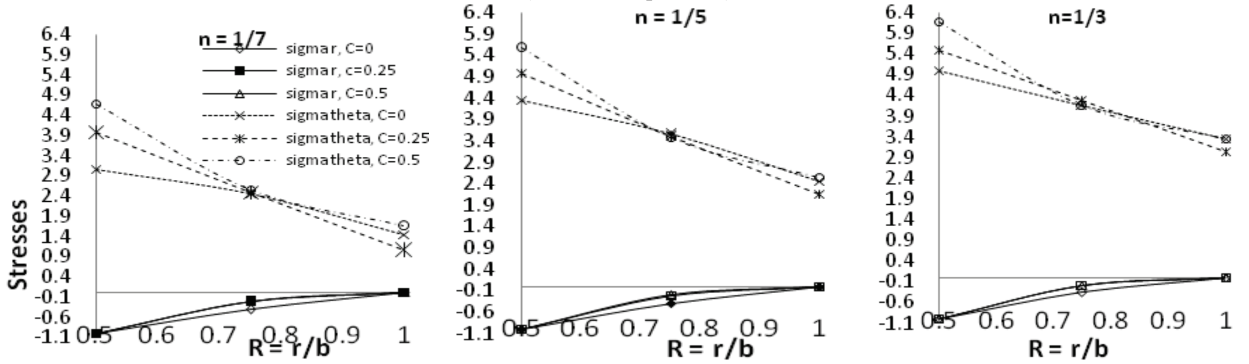


Figure 3. Creep stresses in non-homogeneous ($k = 0$) spherical shell along radii ratio $R = r/b$.

(without temperature)



(temperature $\Theta_1 = 0.5$)

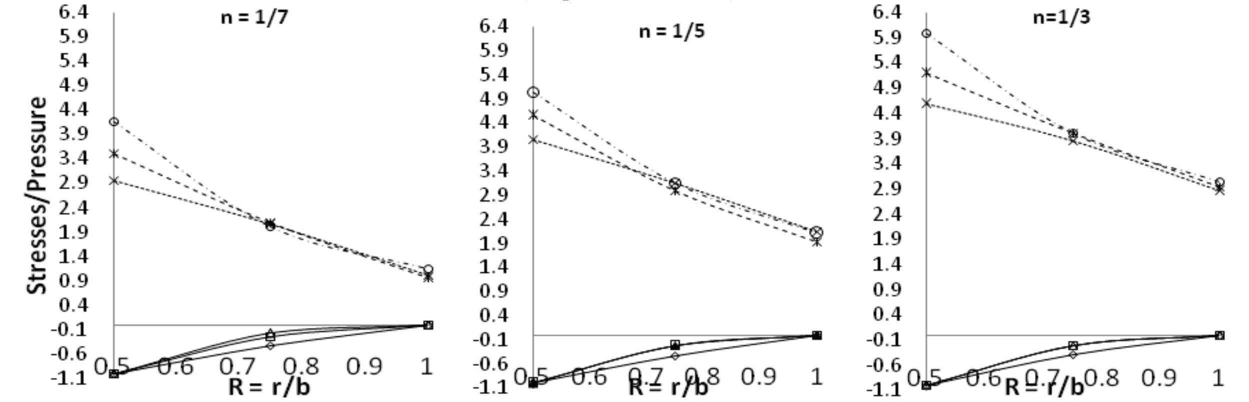
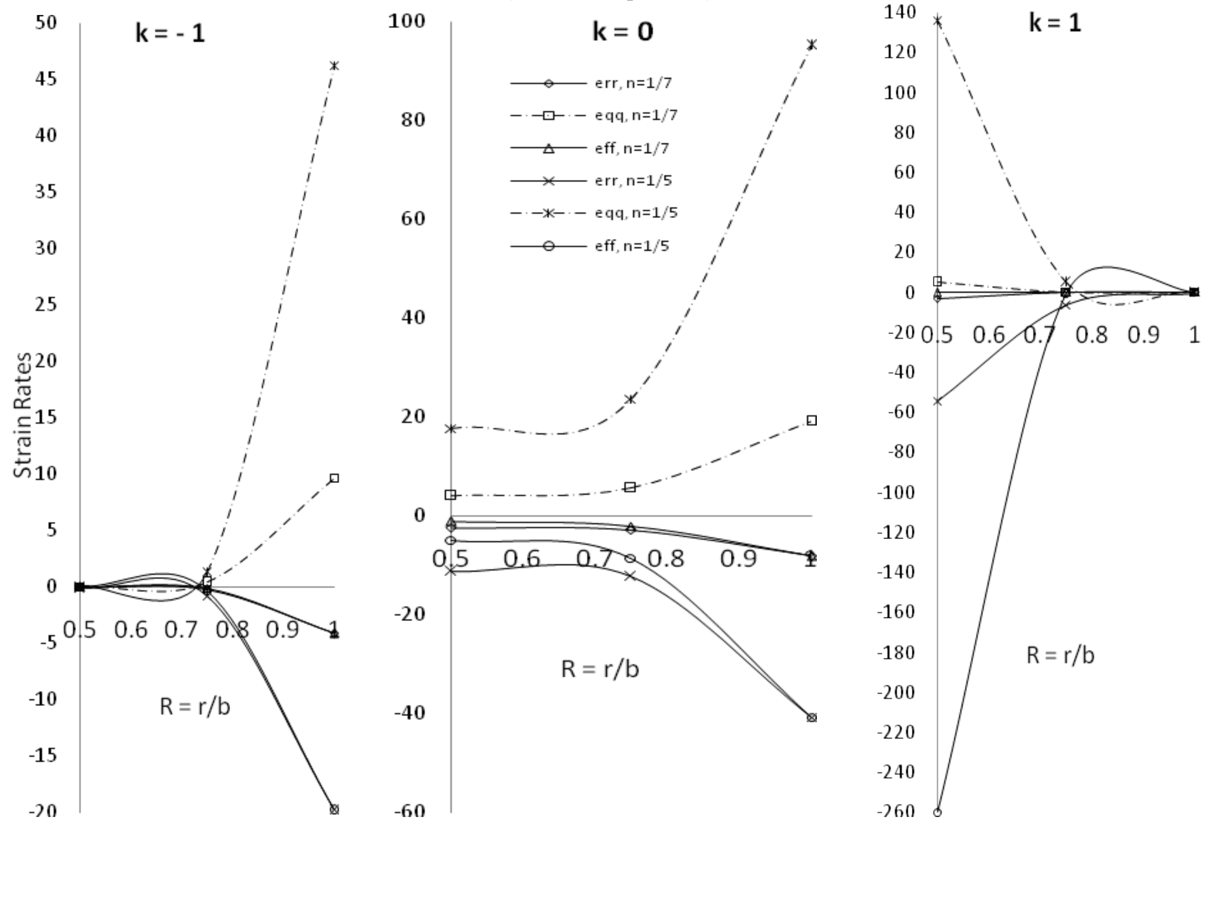


Figure 4. Creep stresses in non-homogeneous ($k = 1$) spherical shell along the radii ratio $R = r/b$.

(without temperature)



(temperature $\Theta_1 = 0.5$)

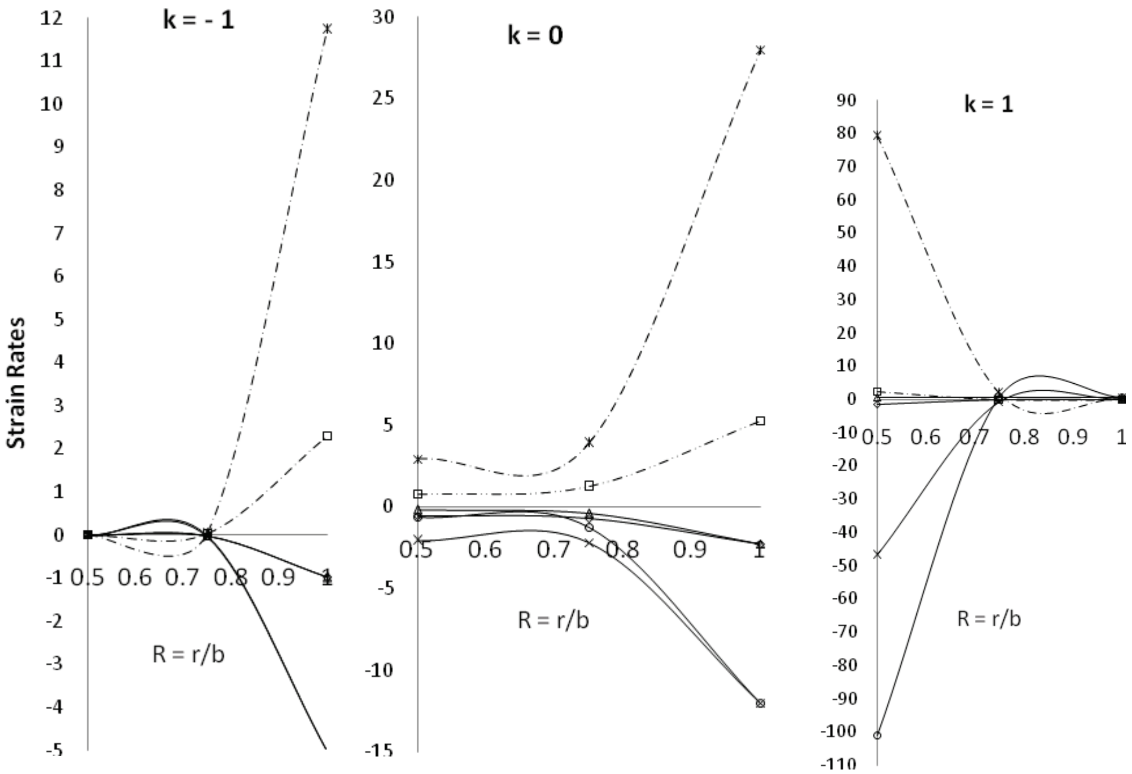


Figure 5. Strain rates in non-homogeneous spherical shell along the radii ratio $R = r/b$, for $C = 0.25$.

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