THE TEMPERATURE GRADIENT EFFECTS ON THE CREEP BEHAVIOR OF STRUCTURES

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ABSTRACT

In this paper the effect of temperature gradient has been studied on the thermal stress distribution and creep stress-strain redistribution over selected structures using uncoupled Finite Element based numerical analysis. For this purpose the steady state temperature gradient has been obtained over a super heater pipeline support. The temperature profiles for the pipe and the support have been used as input data to obtain initial thermal stress distribution and creep stress-strain redistribution over the plate. It has been shown that the structural behavior is severely affected by the existing temperature gradient. This is due to the exponential relationship between temperature and creep strain rate. Also, the results show that by ignoring the existing temperature gradient, the predicted creep lifetime would be erroneous. Therefore, the proposed method is recommended to predict the creep behavior of the structures.

Introduction

The general trend in designing modern thermo-mechanical system is to increase the temperature of the hot source as much as possible. Therefore, creep and structural behavior at high temperature is becoming a major concern. In resent decades, the methods to analyze creep behavior of the structures/materials have been improved significantly. For this purpose, improvements have been made in three fields [1-3]: a) developing more realistic constitutive equations; b) carrying out more tests to produce accurate constitutive parameters; c) improve or modify methods to analyze creep behavior to reduce the simplifying assumptions. The first and second methods require expensive and time-consuming tests. They also lead to mathematically complicated equations, which are hard to deal with. This can be seen by comparing simple Norton equation [4]:

$$\varepsilon_c = A\sigma^n t^m \exp(-\frac{Q}{RT}) \qquad (1)$$

with more complex form proposed by Dyson [5].

$$\frac{d\varepsilon}{dt} = A\frac{1}{(1-\omega_1)(1-\omega_2)^n}\sinh(B\sigma) \qquad (2)$$

where ε_c is the creep strain, σ is the stress, Q is the activation energy, R is Boltzmann's constant, T is the absolute temperature, t is the time, ω_1, and ω_2 are state variables, and the other symbols are material constants.

In this paper the third method has been used, which is to increase the accuracy of the solution method based on the physics of the problem. The creep behavior of a structure/material is a power function of stress and temperature. Therefore, by predicting temperature profile at the structure accurately, the creep behavior and time-dependent stress-strain redistribution would be more realistic

In most of the classic creep analysis [5-8], the temperature has been assumed to be constant. However, as it can be seen in Eq.(1) the temperature profile plays a major role in creep strain rate. In addition, the existing thermal boundary conditions usually cause large temperature gradient through out the structure, which affect its creep behavior significantly. The existing temperature gradient also cause thermal stresses; and therefore, the effect of thermal gradients on structures can be significant. If large thermal gradients exist in steady-state operations, thermally induced stresses will exist [1] in addition to the mechanical loads. The combination or mutual effects of temperature gradient and stress redistribution may lead to differing final stress-strain states through time and a reduced creep life-time to that calculated for the structure using a constant temperature. By ignoring these facts, the predicted creep behavior would be erroneous.

In this paper, a high-pressure steam pipe-support for a steam power-plant super-heater has been selected as a typical structure. Firstly, the creep behavior of the plate has been predicted assuming constant average temperature. Secondly, the temperature profile of the plate has been obtained using FE based method. The output of this stage has been used as the initial temperature conditions to study the creep behavior of the plate. The uncoupled thermo-mechanical analysis of the structure has been carried out using the FE based software ANSYS.

Finite Element Model

To study the importance/effects of the temperature gradient on the elasto-creep behavior of a structure, an AISI 316 steam-pipe support has been selected. This support is used in the super heater of a steam power-plant. Its dimensions are 0.4x0.6x0.05 m with central hole of 0.1 m radius. The existing boundary and initial conditions are presented in Fig. 1. This figure also shows the FE mesh, which has been used in this study.

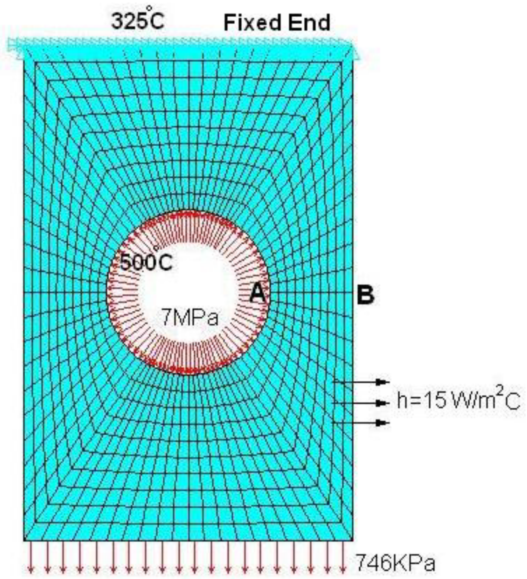

Figure 1. The FE Mesh-model and the boundary conditions for the steam-pipe support

The element types: thermal-plane 8-node; and, structural-plane 8-node have been used for the thermal and mechanical analysis, respectively. The physical properties of AISI 316 have been listed in table 1. At the first stage, the steady-state energy equation:

$$\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}=0 \tag{3}$$

has been solved based on the existing thermal boundary conditions using the FE method. The temperature profiles presented in Fig. 2, which has been obtained at this stage, have been used as an input data in the second stage.

Table 1. The physical properties of AISI 316 stainless steel

E (Elastic Modulus)	ν (Poisson Ratio)	α (Thermal Expansion)	K (Thermal Conductivity)
190e9 (Pa)	0.305	17.3e-6	19 W/mc°

Constitutive Equations

A) Uni-axial form:

Different types of constitutive equations have been proposed in the literature [9]:

$$\varepsilon_c = A\sigma^n t^m \exp(-\frac{Q}{RT}) \tag{4}$$

$$\varepsilon_c = C\sinh(\alpha\sigma)(1+bt^{1/3})e^{kt} \exp(-\frac{Q}{RT}) \tag{5}$$

$$\varepsilon_c = D\exp(\beta\sigma)\sum_j a_j t^{m_j} \exp(-\frac{Q}{RT}) \tag{6}$$

The Norton-Baily equation (4) has been widely used as its advantages and flexibility become appreciated [4,9]. The creep analysis carried out in this paper using this equation. Both the primary and secondary creep have been taken into account. Although, the tertiary stage is important, but due to its short time, it has been ignored in this study. The physical parameters for the Norton Eq. (4) for AISI 316 are presented in table2.

Table 2. The physical parameters for the Norton Eq. (4) for AISI 316 stainless steel [3]

n	1.7371
A	1.3826e-5
m	-0.94
Q	556 KJ/mol

B) Multi-axial form:

The uni-axial form of the Norton equation (Eq. (1)) can be changed into the multi-axial form using following assumptions:

1) The experimental observations carried out by Johnson, Henderson and khan [10] show that creep strain are octahedral shear strain dependent; 2) The material is isotropic; 3) The principal stresses and strains are co-directional; 4) Creep strains are hydrostatic stress independent; 5) The model satisfies the dilatation;

Based on the above assumptions, the multi-axial form of the constitutive equation is:

$$\dot{\varepsilon}_{ij} = \frac{3}{2}\frac{S_{ij}}{\sigma_e}\dot{\varepsilon}_e \tag{7}$$

where $\dot{\varepsilon}_e = (\frac{2}{3}(\dot{\varepsilon}_{ij}\dot{\varepsilon}_{ij}))^{1/2}$ and $\sigma_e = (\frac{3}{2}(S_{ij}S_{ij}))^{1/2}$ are effective strain rate and stress, respectively. The $S_{ij} = \sigma_{ij} - \frac{1}{3}\sigma_{kk}\delta_{ij}$ is deviatoric stress and $\dot{\varepsilon}_{ij}$ is the creep strain rate.

Analytical Solution

Although the geometry of the plate with central hole is a simple one, and its elastic-plastic behavior has been studied in the literature [7,8], but the use of closed form equations such as:

$$\dot{\Sigma}_r = \frac{1}{1-\nu^2}[I_2 + I_3 - \frac{I_0}{(1-X_0^{\ 2})}(1-X^2)] \tag{8}$$

$$\dot{\Sigma}_\theta = \frac{1}{1-\nu^2}[I_2 + I_3 - \frac{I_0}{(1-X_0{}^2)}(1+X^2) - (1-\nu^2)\dot{V}_\theta] \tag{9}$$

where

$$I_0 = (I_2 + I_3)_{X=X_0}$$

$$I_2 = -\frac{(1-\nu^2)}{2}\int_1^X \frac{(\dot{V}_r - \dot{V}_\theta)}{X} dX$$

$$I_3 = \frac{(1-\nu^2)}{2} X^2 \int_1^X \frac{(\dot{V}_r + \dot{V}_\theta)}{X^3} dX$$

and $\sum_{ij} = \sigma_{ij}/\sigma_0$, $V_{ij} = \varepsilon_{ij}/\varepsilon_0$, $X = a/r$, a is the hole radius and ε_0 is reference strain rate, would be difficult in practice. The use of these equations would be more complicated if one introduces the temperature gradient throughout the structure. Therefore, the FE based numerical method has been used in this study.

Results

In this paper, to show the complex interaction between the temperature gradient and creep stress and strains, initially, the support was analyzed assuming the constant mean temperature of (325+500)/2=412.5. In the second stage, the heat transfer equations have been solved using boundary conditions shown in Fig. 1. The temperature profiles and its gradient have been obtained over the plate. As it can be seen in Fig. 2, vigorous temperature gradient in the top half of the plate leads to severe creep strain rate. In addition, due to this temperature gradient, large amount of initial thermal stresses have been produced which create different pattern of creep strain.

Fig. 3 shows the stress distribution σ_y in A-B direction in the support (refer to Fig. 1). In Fig. 3, stress distribution in y direction has been presented in two cases of analyses i.e. a) constant mean temperature; and, b) applying temperature gradient conditions in times t=0 and t=10,000 hours. As it can be seen, in the case of constant temperature, creep stress redistribution is very small and there is insignificant difference between σ_y at t=0 and t=10,000 hours. While, for the second case, the amount of σ_y redistribution between t=0 and t=10,000 hours is significant due to the presence of existing large temperature gradient.

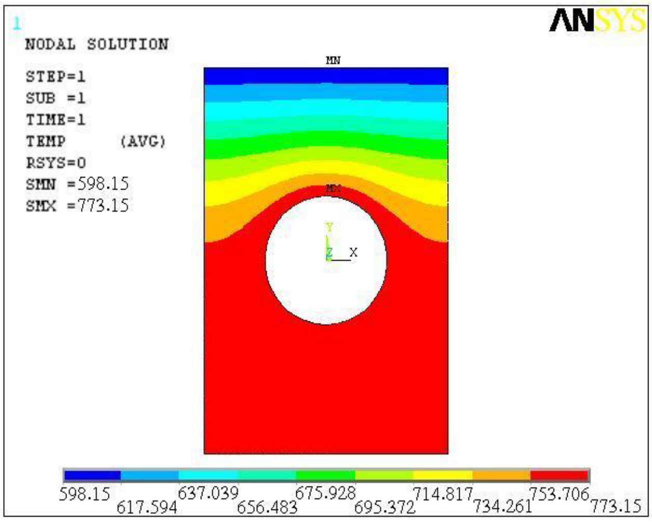

Figure 2. The temperature profile throughout the plate showing the existing large temperature gradient obtained using FE analysis

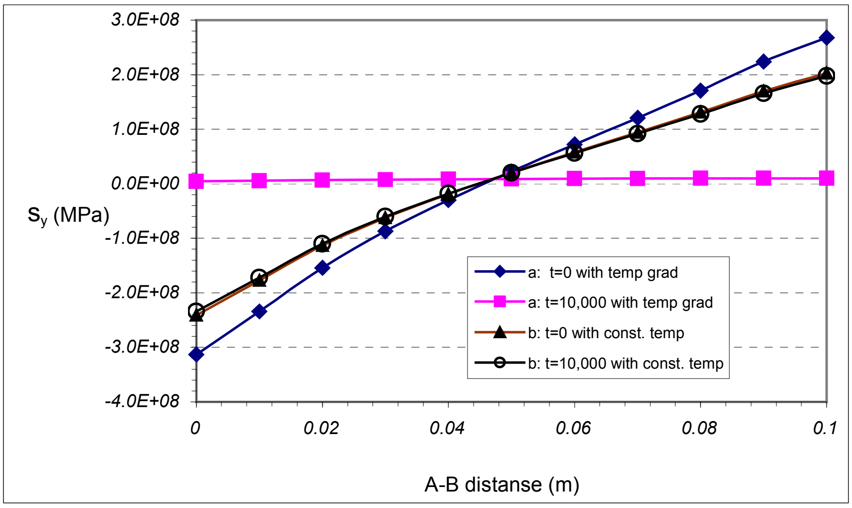

Figure 3. The stress redistribution σ_y in A-B direction of the support: a) at the presence of temperature gradient; and, b) constant temperature

Fig. 4 shows the effective stress redistribution profile in the A-B direction on the support. As it can be seen, in the case of constant temperature condition, creep stress redistribution at time t=10,000 hours is negligible. While, in the existence of temperature gradient, the effective stress changes significantly due to the creep strain during time t=10,000 hours.

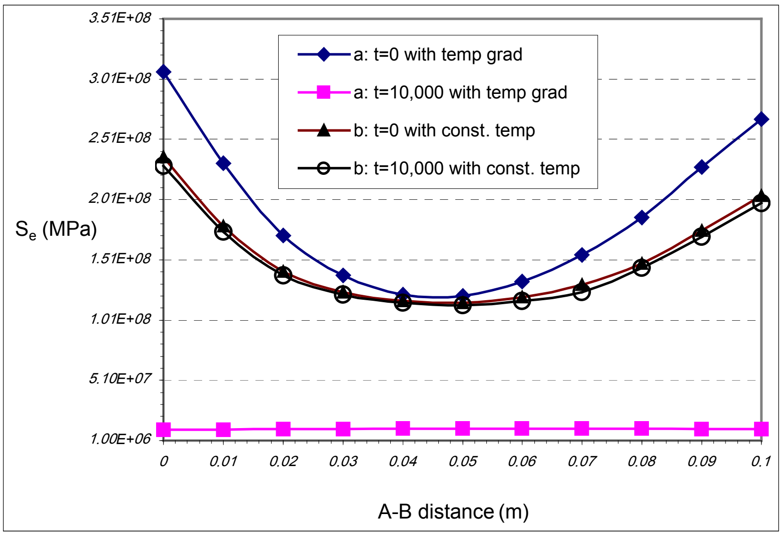

Figure 4. The effective stress distribution in the A-B direction of the support: a) at the presence of temperature gradient; and, b) constant temperature

In Fig. 5(a), creep strain distribution in y direction is shown in the A-B on the plate-support for the case of constant temperature condition. Figure 5(b) presents the creep strain distribution in y direction on the plate-support for the case with temperature gradient. It can be seen that, the creep strain pattern in the second case differ completely comparing with those obtained for the first case, and after 10,000 hours the maximum amount of creep strain has reached to 1.8e-5 and 5.1e-3 for the first (Fig. 5(a)) and second (Fig. 5(b)) cases respectively.

In Figure 6, the effective creep strains for the above mentioned two cases t=0 and t=10,000 hours have been presented in semi logarithmic axes. As it can be seen, in constant temperature conditions, strain distribution due to creep is very small and its amount changes from 7.95e-10 to 2.32e-5. While, at the presence of temperature gradient condition, the accumulated effective creep strain is very considerable and reaches to 5.10e-3. In Figures 7(a) and 7(b), the creep strain profiles have been shown over the support-plate after 10,000 hours for the constant temperature condition and the case of applying temperature gradient, respectively. As it can be seen from these profiles, neglecting the temperature gradient and assuming constant mean temperature leads to considerable error in estimation the amount of creep strain and stress redistribution.

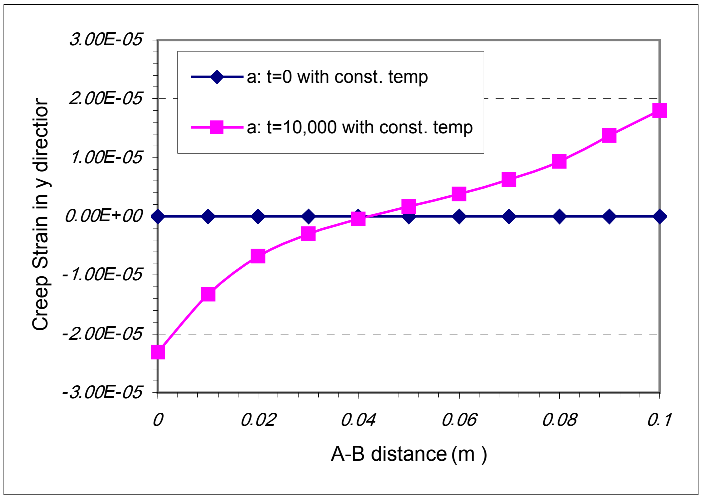

Figure 5(a). Creep strain distribution in y direction in the A-B direction from the support for constant temperature

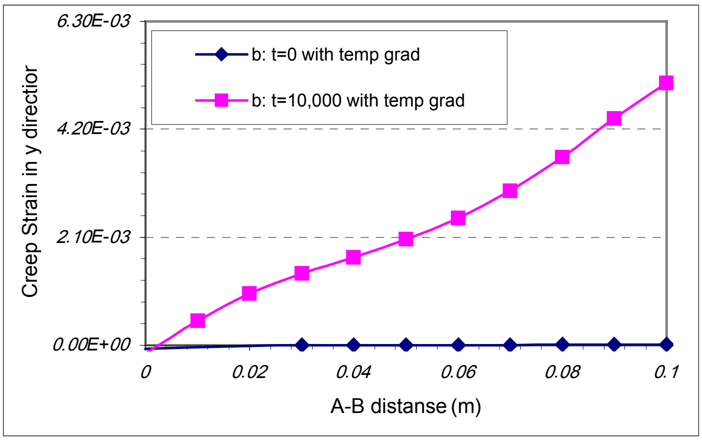

Figure 5(b). Creep strain distribution in y direction in the A-B direction from the support for temperature gradient

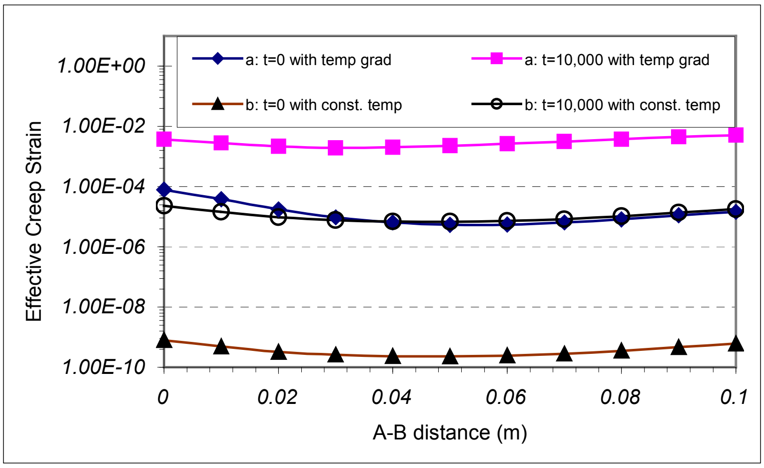

Figure 6. The effective creep strain for a: with temperature gradient and b: constant temperature in the A-B direction from the support

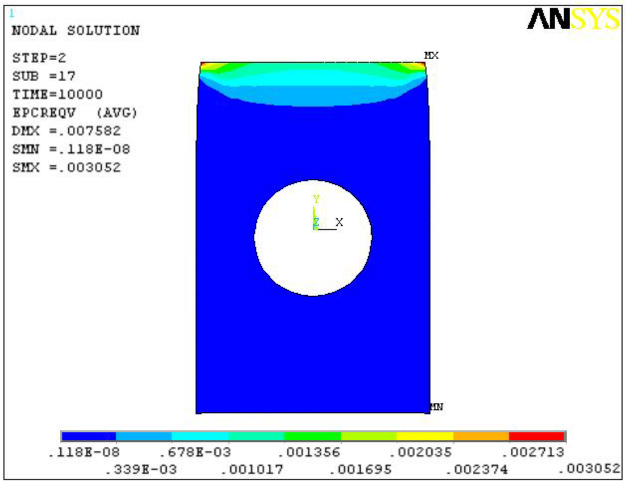

Figure 7(a). The creep strain profile for the case of constant temperature analysis at t=10,000 hours

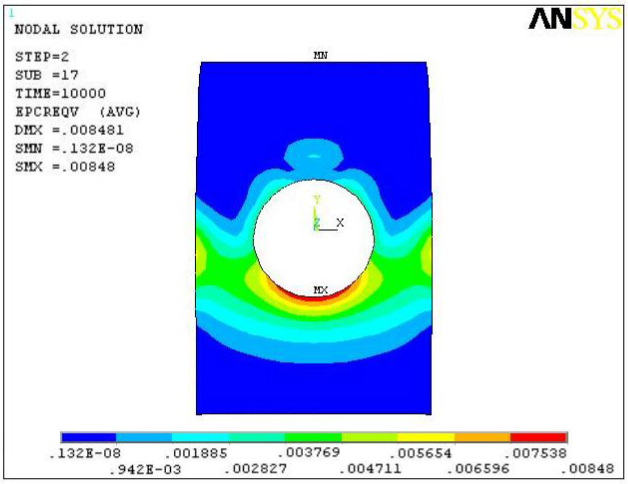

Figure 7(b). The creep strain profile with applying temperature gradient at t=10,000 hours

Figures 8(a) and 8(b), show the creep strain change-history curves for point A on the support (ref. Fig 1) for two cases of analyses (i.e. Fig 8(a) for constant temperature; and, Fig 8(b) for applying the temperature gradient condition) respectively.

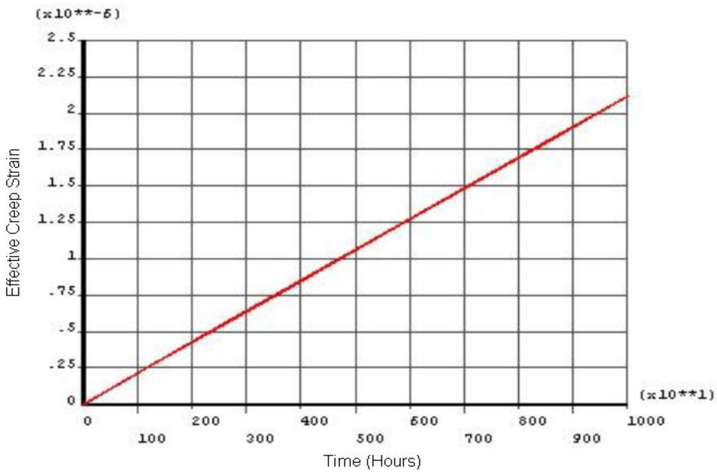

Figure 8(a). The effective creep strain for point A of the support for the case with constant temperature analysis

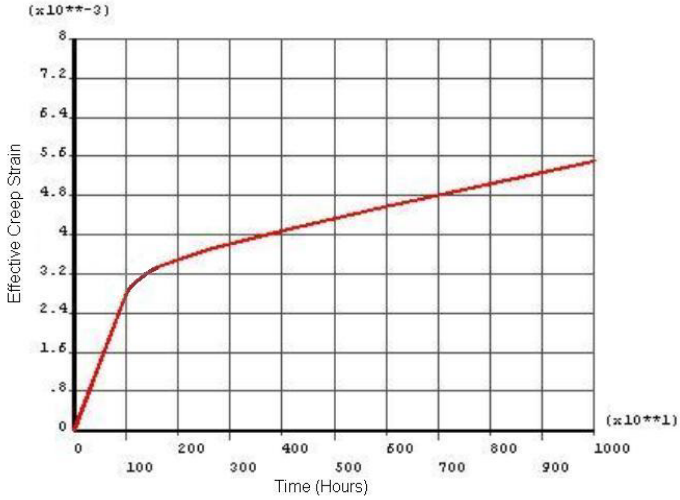

Figure 8(b). The effective creep strain for point A of the support for the case of applying temperature gradient

As it can be seen, temperature gradient has considerable and pronounced effect on the creep strain rate in time and its amount decreases after nearly 1,200 hours due to the presence of temperature gradient. In addition, it can be seen that the accumulated amount of creep strain after 10,000 hours for two different analyses (i.e. constant temperature and with temperature gradient) are 2.32e-5 and 5.10e-3, respectively. This pronounce difference show the effect of the temperature gradient and its major role on creep strain and stress redistribution.

Conclusions

The redistribution of the stresses and creep strains in steam pipe-support has been calculated using FE based method. The results have been obtained by taking into account the effect of the existing temperature gradient. The results have been compared with those, which have been obtained using constant average temperature. It has been shown that more complex interactions exist as a result of temperature gradient and final stress state and creep strains differ significantly with those, which have been obtained using constant temperature. It can be concluded that large temperature gradients should be taken into account in creep analysis of the structures otherwise the results would be erroneous.

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