Creep Buckling Analysis on Petroleum Furnace Tube Subjected to High Temperature Loading Based on ABAQUS

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Abstract. This paper presents a finite element methods to simulate creep buckling phenomenon of petroleum furnace tube under external pressure with the petroleum furnace tube subjected to high temperature loading as the research object. In this paper the furnace tube is predigested as a finite-length cylindrical shell simply supported at both ends. Based on creep aging theory, considering the effect of temperature and service time on the material performance of petroleum furnace tube, the creep buckling ultimate load is acquired from eigenvalue buckling analysis by selecting linear perturbation buckling step. Parametric analyses and buckling analysis are conducted to investigate the effect of length-radius ratio, radius-thickness ratio and temperature on the creep buckling ultimate load of cylindrical shell. Finally, the finite element predictions are obtained and are compared with Mises results. It is found that they are in good agreement, validating the finite element simulation.

Keywords: Petroleum furnace tube; Creep; Buckling; Aging theory; Finite element analysis.

1. Introduction
A large number of furnace tube failure examples show that high temperature creep and buckling are the main causes of damage to petroleum furnace tubes [1]. Scholars at home and abroad have been studying creep buckling since the 1940s, and have made great progress. Benoit and Hoff performed creep buckling experiments on simply supported flat rectangular plates, and determined the creep law of the material at 600°C[2]. Yu Jinyun studied the creep buckling of linear viscoelastic compression bars, and obtained analytical expressions of creep stable load and critical load[3]. Xue proposed the failure mechanism of an infinitely long cylindrical shell under external pressure based on the experimental results of Kyriakodes. It is considered that for an infinitely long cylindrical shell, buckling occurs in a part of the entire structure, rather than the presumed buckling occurs in the entire cylindrical shell[4]. Chai Wei carried out stability analysis of thin-walled cylinders under external pressure under local radial loads, and obtained empirical formulas for various structural parameters and local radial critical loads under external pressure[5]. Combescure proposed a simplified method for predicting creep buckling and analyzed the creep buckling time of a cylindrical shell subjected to external pressure [6].

2. Basic Theory
Consider a cylindrical shell, which is subjected to the out-of-plane normal pressure $q$, the thickness of the shell is $h$, the radius from the middle of the shell to the center of the shell is $R$, and the total length...
of the pipe is \( L \) (the Young's modulus of elasticity is \( E \), Poisson’s ratio is \( \mu \)). According to the creep aging theory, the aging theory formula can be obtained:

\[
\varepsilon_c = A\sigma^n t^m = \sigma^n \Omega(t)
\]  

(1)

Where \( \varepsilon \) is the creep strain, \( A, m, n \) are material parameters related to time and temperature, which are determined by creep test data.

For a cylindrical shell, when creep occurs, the material will be damaged, and the Young's modulus of elasticity and Poisson’s ratio will change. The law is:

\[
E_c(t) = \frac{E}{1 + \sigma^{n-1} \Omega(t)E}, \quad \mu_c(t) = \frac{\mu + \frac{1}{2} \sigma^{n-1} \Omega(t)E}{1 + \sigma^{n-1} \Omega(t)E}
\]  

(2)

Where \( E, \mu \) is the initial Young's modulus of elasticity and Poisson’s ratio, and \( E_c(t), \mu_c(t) \) is the Young's modulus of elasticity and Poisson’s ratio after \( t \) time of creep action.

For a cylindrical shell subjected to an out-of-plane normal distributed pressure \( q \), the relationship between the stress \( \sigma \) and the external pressure \( q \) is:

\[
\sigma = \frac{qR}{2h}
\]

3. Finite Element Model

The tensile shell element provided by ABAQUS finite element software is used to establish the model, create the elastic modulus and Poisson's ratio material properties, select the linear perturbation buckling analysis step, perform the eigenvalue buckling analysis, and apply the out-of-plane normal distribution pressure \( q = 1 \)Mpa. Using the PINNED boundary condition, the 4-node quadrilateral reduced integral shell element S4R is selected for meshing. The grid division layout is divided by 5mm cloth, as shown in Figure 2.

4. Analysis of Examples

In this section, ABAQUS finite element software is used to perform a creep buckling analysis on a cylindrical shell made of A149 steel. Table 1 records the creep material parameters of A149 steel measured by B.A. Fields [7]. In addition, Young's modulus of elasticity \( E = 171.561 \) GPa and Poisson’s ratio \( \mu = 0.3 \).

| Creep theory | Material parameters |
|--------------|---------------------|
| \( \varepsilon_c = A\sigma^n t^m \) | \( A \) |
| | \( 10^{-(6.10+0.00573xT)}(T \leq 500\degree C) \) |
| | \( m \) |
| | \( n \) |
| \( 10^{-(13.22-0.00851xT)}(T \geq 500\degree C) \) |
| \(-1.1 + 0.0035 \times T\) | 2.1 + 0.0064 \times T |
4.1. Creep Buckling Modes of Cylindrical Shells

Figure 2 simulates the effects of the aspect ratio, radius-thickness ratio, and temperature on the buckling mode of a cylindrical shell after 100 hours of creep. It can be seen from the figure that when the temperature and the radius-thickness ratio are constant, the larger the aspect ratio is, the smaller the wave number is when the cylindrical shell is buckling; when the temperature and the aspect ratio are constant, the larger the radius-thickness ratio is, the more wave number is formed when the cylindrical shell is buckling; and the buckling mode of the cylindrical shell is independent of temperature.

Figure 2. Effects of aspect ratio, radius-thickness ratio and temperature on buckling modes of cylindrical shells.

4.2. Effect of L/R Ratio

Set the temperature to 350°C, the radius-thickness ratio to 100, and the aspect ratio to 4, 8, and 16. Change the service time and observe the effect of the length-to-diameter ratio on the creep buckling limit load when creep occurs, as shown in Figure 3.

It can be seen from the figure that when creep occurs, the larger the aspect ratio, the longer the service time and the smaller the creep buckling limit load.
4.3. Effect of R/h Ratio
Set the temperature to 350°C, the aspect ratio to 4, set the radius-thickness ratio to 100, 200, and 300. Change the service time and observe the effect of the radius-thickness ratio on the creep buckling limit load when creep occurs, as shown in Figure 4.
It can be seen from the figure that the creep buckling limit load decreases with the increase of the radius-thickness ratio and the increase of the service time when creep occurs.

4.4. Effect of Temperature T
Set the aspect ratio to 4 and radius-thickness ratio to 100, change the service time, and observe the effect of temperature on the creep buckling limit load at different times of creep action, as shown in Figure 5.
It can be seen from the figure that the creep buckling limit load is more sensitive to the temperature effect at different creep action times, and it decreases continuously as the temperature increases.

5. Comparison of ABAQUS Solution and Theoretical Solution
In order to verify the correctness of ABAQUS finite element analysis, the above finite element results are compared with Mises solutions, as shown in Figures 6 (a), (b), (c).
It can be seen from the figure that the change trend of the theoretical solution and the change law of the ABAQUS solution remain highly consistent, so the rationality and effectiveness of the ABAQUS finite element solution can be verified.
Figure 6. Comparison of ABAQUS solution and theoretical solution

6. Conclusion
Through the above analysis, the following conclusions can be drawn:

(1) Under the influence of high temperature creep, material parameters such as Young's modulus and Poisson's ratio will change. The longer the creep action time, the lower the strength of the material and the lower the ultimate buckling load.

(2) Structural parameters such as aspect ratio and radius-thickness ratio determine the buckling mode of a cylindrical shell during creep, and temperature accelerates the rate of creep. Both of them have a great influence on the ultimate load of creep buckling. On the whole, the larger the aspect ratio, the larger the radius-thickness ratio, and the higher the temperature, the smaller the ultimate buckling load.

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