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STRESS ASSESSMENT BASED ON OVALITY AND THICKNESS ASYMMETRY FOR AN INTERNALLY PRESSURIZED PIPE ELBOW AT HIGH TEMPERATURE

Hong XU, Li DUAN, Naiqiang ZHANG
Key Laboratory of Conditioning and Control for Power Plant Equipment, Ministry of Education, School of Energy and Power Engineering
North China Electric Power University, Dewai, Beijing 102206, P. R. China
Phone: +86-10-51963937, Fax: xxxx +86-10-80798324
E-mail: xuhong@ncepubj.edu.cn

Guoyue LIU
Huaneng Power International Inc. ,Beijing 100031, P. R. China

ABSTRACT

In this paper the material creep behavior and multiaxial stress state of high temperature pipe elbow were investigated. The stress distribution in the pipe elbow during creep is discussed. The maximum stress area of pipe elbow transfers from inner wall to outer wall during creep. The ovality and the different initial thickness asymmetry of steam pipe elbows subjected to a uniform internal pressure at high temperature are calculated with Finite Element Analysis (FEA). The initial ovality and wall-thickness play a very large role in stress distribution in the elbows, and vary with time during creep. That explains the transfer of stress distribution in the elbows. Based on influence of ovality and thickness an analytical model to calculate equivalent stress of elbow through straight pipe stress is presented.

Keywords: Ovality, Pipe Elbows, Creep, Thickness, FEA

1. INTRODUCTION

The Chinese electric power industry has been developing greatly and rapidly in recent three and four years. In order to reduce air pollutant emission rates and enhance energy efficiency of fossil fired power plants supercritical and ultra supercritical units with the steam temperature and the steam pressure up to 600℃ and 30MPa will become predominate one in the future decade. In such a situation it is necessary to ensure the safety and the reliability of power generation equipment during their operation, especially, for high temperature pipelines connecting the boiler and the steam turbine.

At high temperature an internally pressurized pipe with large diameter used in supercritical and ultrasupercritical unit has shown its viscoelastoplastic material characteristics. In these applications the pipe is subjected to high temperature and high internal pressure, which will produce a tensile stress field in pipe and a complicated multiaxial stress state in its elbow. Aside from third party damage, ductile, brittle rupture and slow nucleation up to crack growth taking place at stress or strain concentrations are the dominating creep failure mechanisms. For high temperature pressure vessels, there exists a requirement for accurate methods of creep life prediction. This is particularly the case for major plant components such as steam pipes and tubes. Furthermore, more attention must be paid to pipe bends or elbows which have initial ovality and thickness asymmetry. At this area, the stress distribution is complicated and varies with time due to creep. The analysis of ovality and thickness asymmetry of pipe elbow plays a key role in studying the stress variation and creep damage proceeding (Hyde，1999).

In this paper, finite element analysis (FEA) has been carried out for 90 ° steam pipe bends made from 9Cr-1MoNbV(P91) steels. Based on the distributions of stress and the time-dependent creep strain of pipe elbows the influence of ovality and thickness asymmetry is analyzed and discussed.

2. BOUNDARY CONDITIONS AND MATERIAL PARAMETERS

A local pipe elbow is demonstrated in Fig.1. In order to eliminate boundary condition influence at both ends two straight pipes were attached to both ends respectively. To simulate the actual condition and to simplify the calculation, a boundary condition only with internal pressure and with both ends fixed. During discussion the pipe elbow is under internal pressure up to 23MPa and temperature up to 600℃. Moreover, due to the symmetrical loading it is possible to cut the model of the pipe elbow in its symmetry-plane and reduce computing time and costs.

Before starting the creep calculation, some parameters of material 9Cr-1MoNbV(P91) used in creep analysis have been confirmed by curve fitting method refer to experiment data (Gaffard, 2004).

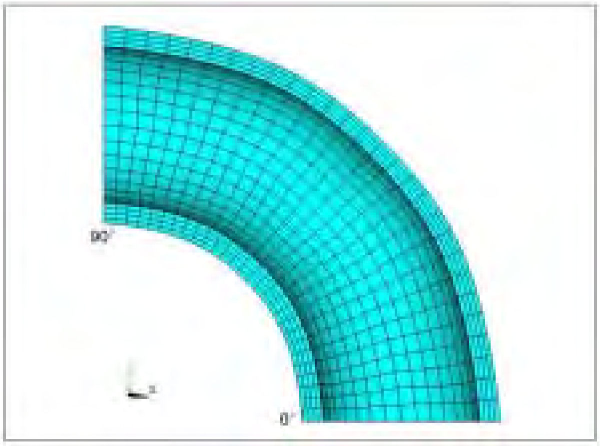

Fig.1 FE geometry model of pipe elbow

3. RESULTS OF FEA

3.1 Stress distribution of elbow

From the results of all FEA calculations it can be found that tangential stress along 45o of the pipe elbow is predominant in the process of creep development. The tangential stress components are much higher than axial and radial stresses. According to creep damage theory, the tangential stress as the principle stress will dominate creep damage. Thus the following analysis concentrates on the first principal stress distribution in the elbow.

At the bend angle 45oareas of the elbow, more attention should be paid due to the factors of ovality and thickness difference. When the creep doesn’t happen (time=0.3h) the inner wall stress is predominant, while the outer wall stress values are largest in the steady-state creep phase (time=8000h), as shown in Fig2 and Fig3.

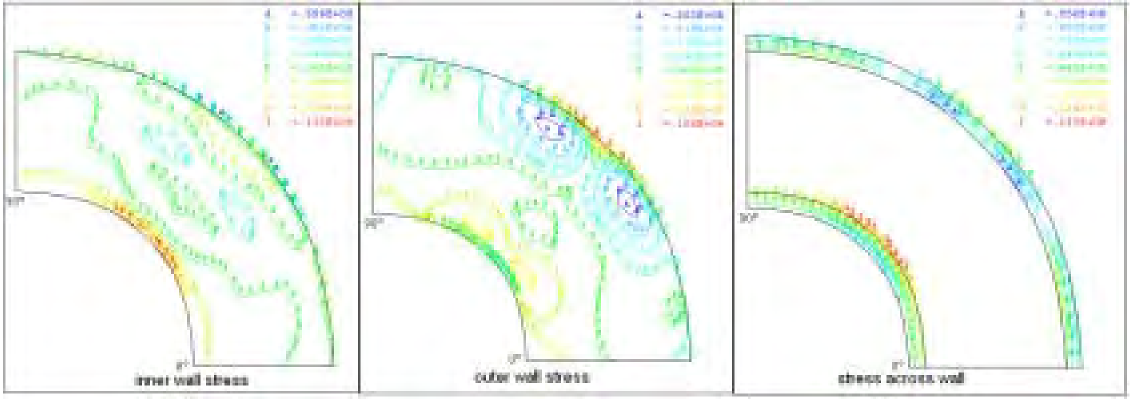

Fig.2 Stress distribution(Internal Pressure 23MPa, time=0)

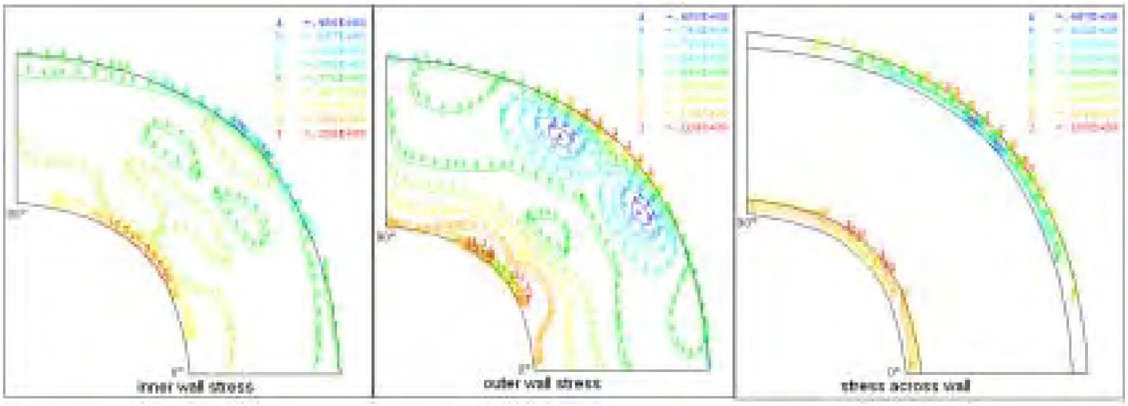

Fig.3 Stress distribution after creep (Internal Pressure 23MPa, time=8000h)

As above figures showed, at the beginning of creep the maximum stress locates in the intrados inner wall areas at bend angle 45o. However, alone with creep loading time the maximum stress point shifts to extrados outer wall areas at bend angle 45oof the pipe elbow, that is, the maximum tangential stress area transfers from inner wall to outer wall during creep. The stress differences between inner wall and outer wall at extrados are much more than intrados. Due to the largest equivalent stress located at bend angle 45oof extrados outer wall of the elbow during pipe operation the strain gauges should be installed. In addition, the extrados wall is usually thinner than intrados at this position. As a result, it is the weakest point where micro-crack exits easily, and becomes a key reference point for on-line monitoring and life prediction.

3.2 The influence of elbow ovality

3.2.1 The change of ovality depending on time

The ovality of elbow is defined as follows:

$$u = 2(D_l - D_s)/(D_l + D_s) \tag{1}$$

where: u represents ovality of elbow, D_l, D_s are the long axis length and the short axis length of ellipse cross section respectively.

Time-dependent ovality is demonstrated in Fig. 4. It means that the section form at bend angle 45o of elbow swells up from ellipse to roundness gradually with the increasing time. The tendency of the results is coincident with the research of Hyde (1998) very well. It can also be observed that a significant reduction in ovality exists during creep. The phenomena are often found for high temperature and high pressure pipeline elbow in period of equipment overhaul in the most of power plant

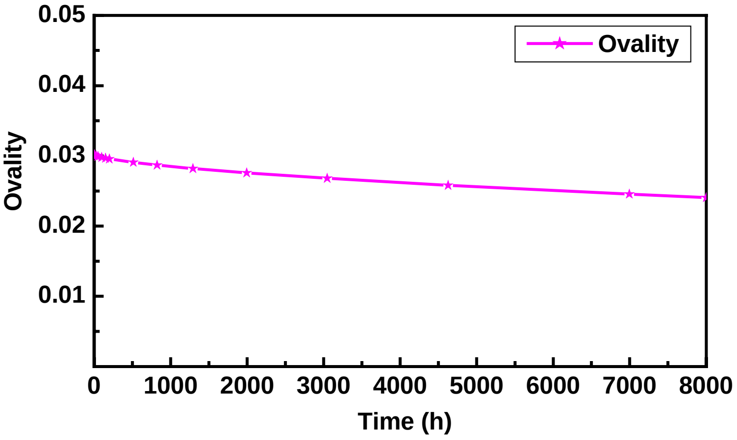

Fig. 4 The ovality variation of elbows depending on time (Internal Pressure 23MPa)

3.2.2 Influence of different ovalities on stress in the elbows

To find the influence of ovalization on von Mises stress in the elbows, FE stress and strain analysis on elbow model with different ovalities is calculated and compared respectively. Initial ovalities changed from 0 to 0.5 with the same wall-thickness are discussed. The relationship between ovality and von Mises stress in inner and outer walls is demonstrated in Fig. 5.

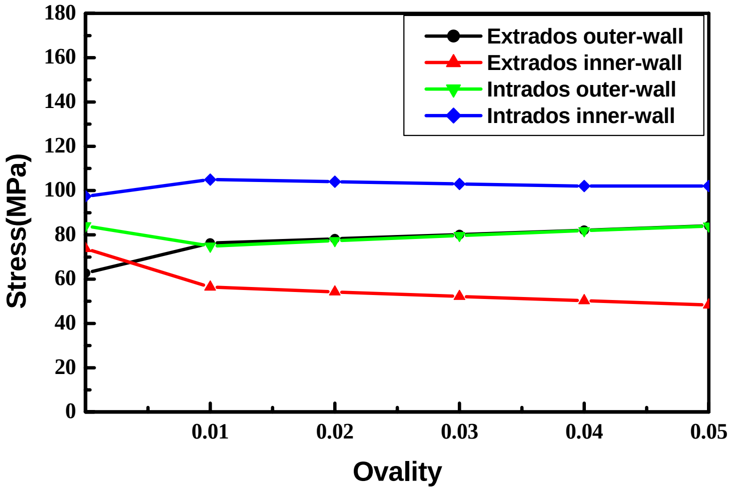

Fig.5 The relation between Von Mises stress and initial ovality (time=8000h)

According to the research results of Hyde (1998) the ovalization will hardly change if the initial ovality is very small in elbow. Fig. 5 shows also an influence of initial ovality on stress in different area of elbow, with respect to roundness section without initial ovality the stress distribution in elbow section changes very slightly during creep. It can be observed that stress in outer wall of elbow with larger initial ovality (such as 0.05) is higher than that of elbow with smaller initial ovality (such as 0.01), while, the inner wall stress has opposite results. Thus, it explains why the initial ovality of pipe elbows must be controlled in the limited range, and why micro-crack comes into being first in the outer wall of pipe elbows.

3.3 Section wall-thickness analysis

3.3.1 The influence of wall-thickness deviation on stress

The wall-thickness ratio v between elbow and straight pipe is defined:

$$v = T_e / T_s \qquad (2)$$

where: v is defined as a wall-thickness ratio of pipe elbow with straight pipe, T_e, T_s represents wall-thickness of elbow extrados and straight pipe respectively.

A group of pipe elbows with same initial ovalities but different thickness ratio are calculated, which thickness ratio changes from 1 to 0.86, as shown in Fig. 6.

The analysis results reveal the linear relations between Von Mises stress and initial thickness ratio. However, extrados and intrados stress have reverse change tendency. The extrados stress increases, while intrados stress decreases. Consequently, the extrados is the most important part of elbow. What’s more, the initial thickness deviation of elbows is a significant factor for stress analysis. So when elbows are made it must be obeyed to control the thickness of elbows in the limited range.

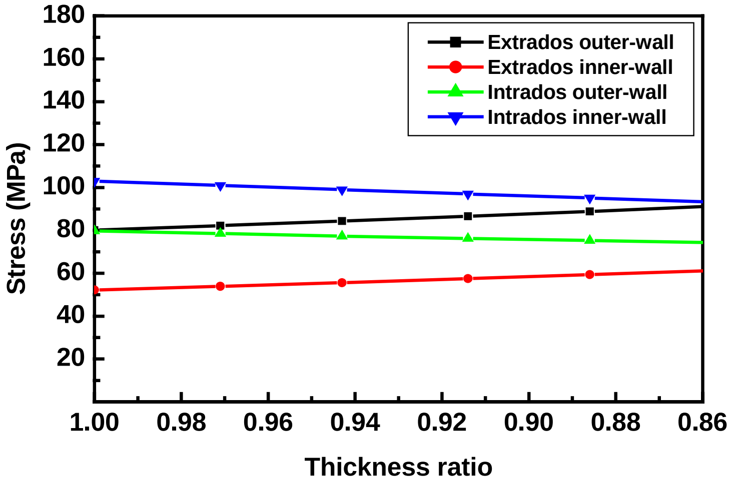

Fig.6 The relationship between Von Mises stress and initial thickness ratio(time=8000h)

3.3.2 The variation of wall-thickness during creep

Usually, the pipe elbow has different wall thickness at extrados and intrados when it's bent. The extrados wall is thin, while the intrados wall is thick, and during creep the two thicknesses vary with time. So by FEA calculation this variation tendency is obtained, as shown in Fig.7.

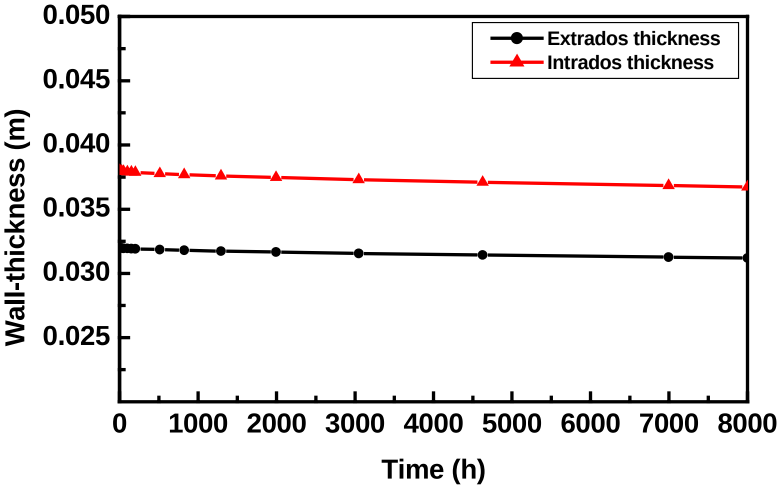

Fig.7 Wall-thickness variation depending on time

As be seen in the Fig.7, the extrados and intrados wall thickness are all reduced following time. The animate deformed shape of pipe elbows in the FEA analysis displays that the section at bend angle 45 ° of elbow becomes swelled and thin gradually. Considering the extrados wall is thinner than intrados at the start, and the first principal stress in extrados is quite great, so the extrados area is the weakness in elbow.

4. STRESS MODEL IN ELBOW

From FE calculation results in the paper a analytical model to estimate the maximal von Mises stress in 45 ° section of elbow on the basis of straight pipe, in which the thickness and ovality change with time. The maximal equivalent stress of elbow can be expressed in following formula,

$$\sigma_e = \frac{\sqrt{2}A}{2(1-u)} \cdot \sqrt{(\frac{\sigma_1}{v} - \sigma_2)^2 + (\frac{\sigma_1}{v} - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2} \qquad (3)$$

where: u is ovality of elbow as same as Eq. 1; v is the wall-thickness ratio of pipe elbow to straight pipe as defined in Eq.2; A is material constant related to radius of elbow and pipe radius, A=1.1715.

In same situation of initial ovality and boundary conditions three cases with the different thickness in extrados and intrados of elbow are compared and verified by means of FEA. Thicknesses of extrados and intrados in three cases are 32mm/38mm, 33mm/37mm and 34mm/36mm respectively. Straight pipe thicknesses of three cases are all 35mm.

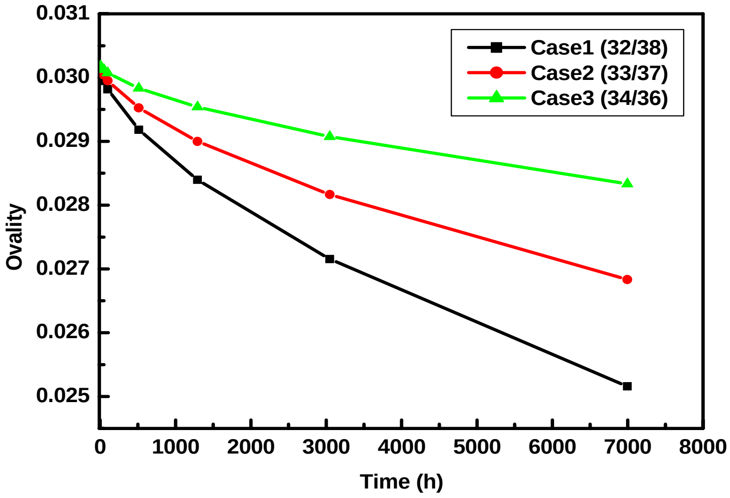

Fig. 8 Ovality comparison of three cases with different thicknesses

In Fig.8 it can be demonstrated that Ovality changes with time are influenced by thickness ratio of elbow. In Fig.9 the stress results obtained from Eq. 3 are coincident with the FEA results. The maximal error is smaller than 1.4%. Eq.3 can be used to calculate the stress of elbow through stress of straight pipe during creep. If three principal stresses of straight pipe, ovality and extrados thickness of elbow are given, the stress of extrados in the elbow can be calculated.

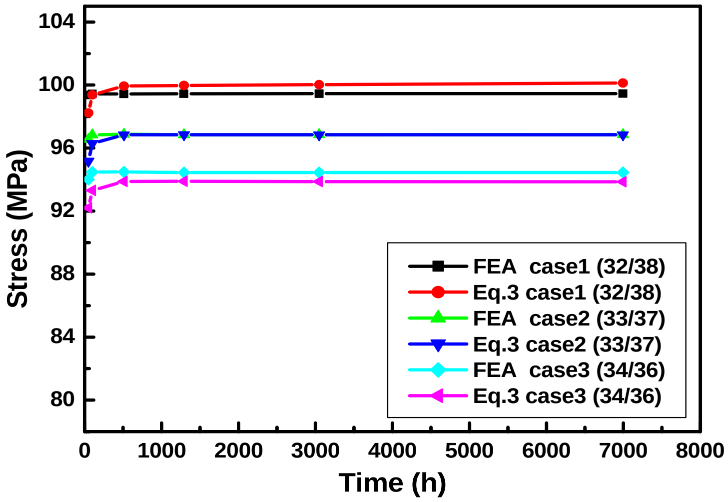

Fig. 9 Stress Comparison between analytical solutions and FEA results

5. CONCLUSIONS

In this paper the stress distribution in the pipe elbows is discussed. The stress in outer wall of elbows increases during creep, and extrados stress is highest. The position of extrados outer-wall at bend angle 45 ° should become as the key monitoring point. The initial ovality and wall-thickness play a very large role in stress distribution in the elbows. It is suggested that the analytical model presented in this paper be used to estimate equivalent stress in pipe elbow through principal stresses in straight pipe in power plant.

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