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A Multifactorial Lifetime Estimation Method for Boiler Components of Coal-Fired Power Plant During Flexible Operations#

JunZheng Zhang[1], Lei Pan[1*], Xiao Wu[1], Junli Zhang[1]

1 School of Energy and Environment, Southeast University, Nanjing, 210096, China

(Corresponding Author: panlei@seu.edu.cn)

ABSTRACT

Coal-fired power units may have safety risks during deep peak shaving and rapid load changing. Therefore, a comprehensive estimating method based on Finite Element Analysis (FEA) and boiler design rules is proposed in this study. Measured data is taken as the boundary conditions for FEA, and the time related restrictions from boiler design rules are used to calculate the primary stress, inelastic strain and creep-fatigue lifetime indicators. The header at the outlet of the final-stage superheater of a 350MW supercritical boiler is analyzed, and the results show that under operating conditions of cold start-up, up to 55% depth of peak shaving and up to 1.4%/min of load change, there is no risk of plastic collapse. Inelastic strain mainly accumulates during start-up process, rather than during peak shaving. Creep-fatigue damage mainly occurs around the fillets of the branch tubes. The fatigue damage is only 0.2% after 30 years operation, with no significant thermal fatigue. But the creep damage is excessive, exceeding the limit after operation of 300 days.

Keywords: Coal-fired power plant, Flexible operation, Lifetime estimation, Finite element, Viscoplastic

NONMENCLATURE

Abbreviations	
BPVC	Boiler and Pressure Vessel Code
FEA	Finite Element Analysis
Max.	Maximum
Min.	Minimum
SCL	Stress Classification Line
Temp.	Temperature, °C
Typ.	Typical
Symbols	
d_i	Inner diameter, mm
d_o	Outer diameter, mm
l	Axial distance, mm
P_b	Primary bending stress intensity
P_L	Local primary membrane stress intensity
P_m	General primary membrane stress intensity

1. INTRODUCTION

Nowadays, in order to absorb more renewable energy and reduce carbon emissions, coal-fired units are usually set up in flexible peaking operation which means deep peak shaving and rapid load changes and give rise to many risks, such as unstable combustion, boiler tube overheating, fatigue, high pollution, etc.[1] Among them, the equipment life damage cannot be ignored in the long run.

The influence of flexible operation on boiler lifetime can be complicated[2]. For example, there will be more severe thermal deviation during deep peak shaving, leading to a higher temperature of boiler tubes[3]. When the load changes rapidly, the control strategy might not stabilize the steam parameters effectively, resulting in the thermal fatigue failure of thick components[4]. Therefore, it is necessary to estimate the lifetime of a boiler to optimize its regulation to guarantee the safety under flexible operating conditions.

There are various researches conducted on the safety of flexible operation. Some researchers have established system models to determine the boundary conditions of components during flexible operation, and estimate their lifetime accordingly[3]. For damage mechanism of critical components, some studies modeled and estimated the lifetime of boiler tubes[5], headers[4] and steam pipes[6]. The lifetime estimating methods are based on various theories, such as fracture mechanics[7], material testing[8], or related standards[9]. There are also other researchers exploring methods to enhance the safety of the units during

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flexible operation, such as energy storage[10] or control[11]. In conclusion, there are various research methods for lifetime estimation, but there is a lack of comprehensive method for the unit components, from operating parameters to the final calculated lifetime.

This study focuses on an overall lifetime estimation for boiler critical components under flexible operation, proposed a multifactorial estimating method based on FEA and boiler design rules. Taking the outlet header of the final-stage superheater of a 350MW supercritical boiler as a study object, its lifetime indicators of primary stress, inelastic strain and creep-fatigue are calculated based on measured data, and the effects of different operating modes on the lifetime are discussed.

2. MATERIAL AND METHODS

To study the impact of deep peak shaving and rapid load changing on the lifetime of critical components in coal-fired power units, a lifetime estimation method based on FEA and boiler design rules is proposed in this study: taking the outlet header of the final-stage superheater as example, the temperature, stress, and strain fields of the equivalent unit of header are first obtained through FEA. Then lifetime damage is estimated using time related restrictions from ASME Boiler and Pressure Vessel Code (BPVC) III.5[12], as shown in Figure 1.

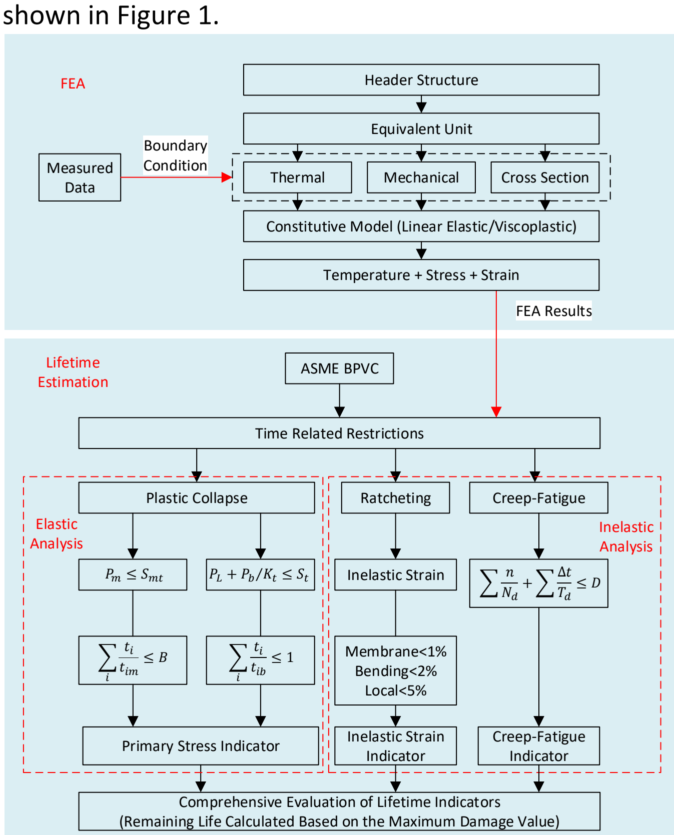


Fig. 1 Lifetime Estimation Method

2.1 Boundary Conditions of FEA

Measured data is taken as the boundary conditions for FEA. For the specified header, the main steam temperature and pressure can be used as the thermal and mechanical boundary conditions for the inner surface of the header wall. The header is long axially, but the branches are in a uniform pattern, hence an equivalent unit is taken as the study object, as illustrated in Figure 2. Pressure boundary conditions are also applied on the cross section of the header and branch tubes to simulate the effect of internal pressure on the end of the header. The same temperature and displacement distributions are applied to each point on the two cross sections. Rigid motion constraints were applied to obtain a unique solution without affecting calculated fields.

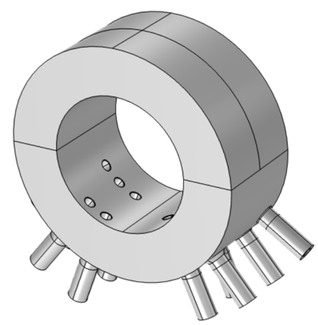


Fig. 2 Equivalent Unit of the Header

2.2 Constitutive Model of FEA

Linear elastic and viscoplastic models are used for the elastic and inelastic analyses, respectively, to calculate the time related terms. The header material is P91, with linear elastic model parameters taken from ASME BPVC II.D[13].

For viscoplastic model, the strain consists of elastic strain tensor $\boldsymbol{\varepsilon}_{el}$, thermal strain tensor $\boldsymbol{\varepsilon}_{th}$ and viscoplastic strain tensor $\boldsymbol{\varepsilon}_{vp}$.

$$\boldsymbol{\varepsilon}=\boldsymbol{\varepsilon}_{el}+\boldsymbol{\varepsilon}_{th}+\boldsymbol{\varepsilon}_{vp} \qquad (1)$$

For Chaboche viscoplastic model[14], $\dot{\boldsymbol{\varepsilon}}_{vp}$:

$$\dot{\boldsymbol{\varepsilon}}_{vp}=\dot{\varepsilon}_{vpe}\frac{\partial\sigma_e}{\partial\boldsymbol{\sigma}}=<\frac{\sigma_e-\sigma_{ys}}{\sigma_{ref}}>^n\frac{\partial\sigma_e}{\partial\boldsymbol{\sigma}} \qquad (2)$$

where $<\cdot>$ are Macaulay brackets, σ_e is the equivalent stress, taken as von Mises equivalent stress in this study, $\dot{\varepsilon}_{vpe}$ is the equivalent viscoplastic strain rate, σ_{ys} is the yield stress, σ_{ref} is the reference stress, and $\boldsymbol{\sigma}$ is the stress tensor.

The isotropic and kinematic hardening are calculated by the Voce rule and Chaboche hardening rule, respectively:

$$\sigma_{ys}=\sigma_{ys0}+\sigma_{sat}(1-e^{-\beta\varepsilon_{vpe}}) \qquad (3)$$

$$\sigma_e = \sigma_e(\boldsymbol{\sigma} - \boldsymbol{\sigma}_b) \tag{4}$$

$$\boldsymbol{\sigma}_b = \sum_i \boldsymbol{\sigma}_{b,i} \tag{5}$$

$$\dot{\boldsymbol{\sigma}}_{b,i} = \frac{2}{3} C_i \dot{\boldsymbol{\varepsilon}}_{vp} - \gamma_i \dot{\varepsilon}_{vpe} \boldsymbol{\sigma}_{b,i} \tag{6}$$

where σ_{ys0} is the initial yield stress, σ_{sat} and β are the isotropic hardening parameters, $\boldsymbol{\sigma}_b$ is the back stress tensor, C_i and γ_i are kinematic hardening parameters. The parameters of the viscoplastic model are taken from literature[15].

2.3 Lifetime Estimation

The time related restrictions in BPVC are taken as lifetime indicators. The corresponding failure patterns are plastic collapse, ratcheting and creep-fatigue failure. To avoid plastic collapse, the primary stress intensity obtained by elastic analysis should satisfy:

$$P_m \le S_{mt} \tag{7}$$

$$P_L + P_b / K_t \le S_t \tag{8}$$

where S_{mt} and S_t are time related stress intensity limits. The restrictions can also be expressed in a form of cumulating lifetime damage:

$$\sum_i \frac{t_i}{t_{im}} \le B \tag{9}$$

$$\sum_i \frac{t_i}{t_{ib}} \le 1 \tag{10}$$

where t_i is time duration, t_{im} and t_{ib} are allowed time durations under specific operating conditions. Such restrictions take degradation of the material into consideration implicitly, and the terms on the left side of the inequality symbols in equations (9-10) are referred to as the primary stress indicator.

To avoid failure due to excessive cumulated inelastic strain (such as from ratcheting effect), the cumulated inelastic strain should be limited less than 1% averaged through the thickness, 2% at the surface after linearization through the thickness, and 5% at any location. The ratio of the cumulated inelastic strain to the limits is referred to as the inelastic strain indicator, which can be expressed as:

$$\frac{\varepsilon_{ie}}{\varepsilon_{\lim}} \le 1 \tag{11}$$

where ε_{ie} and ε_{lim} are inelastic strain and its limit, respectively.

To avoid creep-fatigue failure, the sum of the creep and fatigue damage, which is referred to as the creep-fatigue indicator, should satisfy:

$$\sum_j \frac{n}{N_d} + \sum_k \frac{\Delta t}{T_d} \le D \tag{12}$$

where creep and fatigue damage are calculated in a form of linear superposition, and D is determined by the creep-fatigue damage envelope, which will be discussed later in 4.3.

The maximum value among the three damage indicators (9)-(12) is referred to as the comprehensive lifetime indicator, where i, j and k are used to distinguish the various operating conditions.

3. CALCULATION

3.1 Study Subject and Operating Conditions

The outlet header of the final-stage superheater of a 350MW supercritical boiler is used as the study subject, whose parameters are shown in Table 1.

The measured main steam temperature and pressure serve as the boundary conditions for FEA, covering the process of cold start-up and peak shaving. The operating conditions are shown in Table 2.

The parameters of the main steam and maximum von Mises equivalent stress obtained from elastic analysis, are shown in Figure 3. It can be seen that the major cause of stress is steam pressure, but the thermal stress can induce additional stress and stress amplitude.

Table 1 Header Parameters

Material	Header		Branch Tubes		
	d_i	d_o	d_i	d_o	l
P91/T91	267	457	21	38	54

Table 2 Operating Conditions

Steam Temp.			Min. load	Max. load change rate
Max.	Min.	Typ.		
570	536	570	45%	1.4%/min

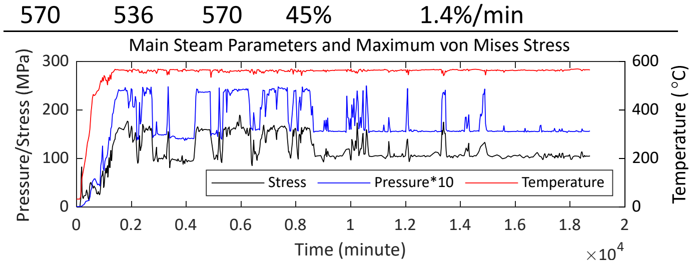
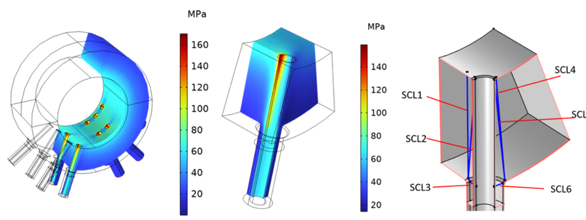


Fig. 3 Main Steam Parameters and Maximum von Mises Stress

3.2 Sub-modeling and Primary Stress Indicator Calculation

Sub-modeling is employed in this study for an increased mesh around the fillets to improve calculating accuracy, with no additional calculation resources. The whole equivalent unit of the header is analyzed as shown in Figure 4 (a). Then a sub-model with only a branch tube and surrounding parts are analyzed separately, as shown in Figure 4 (b), whose displacement and temperature at the cross sections are from the FEA of the whole equivalent unit.

To calculate the primary stress indicator, it's necessary to select the Stress Classification Line (SCL), in order to produce membrane and bending stresses from results of FEA [12]. The typical von Mises equivalent stress contour is shown in Figure 4 (a-b), which indicates highest stress at the fillets, and more uniform stress at other parts. Thus, the SCLs are selected near the fillets and cross the wall, as shown in Figure 4 (c). SCL1 and SCL4 cross the welds and be perpendicular to the header wall, SCL2 and SCL5 connect the fillets and the welds, SCL3 and SCL6 cross the welds and be perpendicular to the branch tube wall.



(a) (b) (c)

Fig. 4 Typical von Mises Stress Contour and SCLs: (a) the Equivalent Unit, (b) the Sub-Model, (c) SCLs

The FEA only takes the effects of steam temperature and pressure into consideration, without other loads such as gravity, constraints to the displacement of the branch tubes, etc. Therefore, no bending stress nor thermal stress is classified as primary stress.

3.3 Inelastic Strain and Creep-Fatigue Indicator Calculation

The other two indicators are also calculated using sub-modeling method, as shown in 3.2. To investigate the accumulation of inelastic strain, the study takes the point with highest equivalent stress, which is on the fillet, as the critical point. Note that the effective Poisson coefficient is taken as 0.5 in the calculation of equivalent strain, for a viscoplastic constitutive model is employed.

For the creep-fatigue damage, the creep damage can be expressed in the form of time integration, allowing for the analysis of creep damage accumulating over time. Fatigue damage is calculated through the linear superposition of a ratio, which is the number of the cycle during operation to the maximum number of the cycle (depending on temperature and stress/strain amplitude).

4. RESULTS AND DISCUSSION

4.1 Primary Stress Indicator

Around the fillets, the maximum primary membrane intensities at SCL 1-6 are 55 MPa, 71 MPa, 53 MPa, 39 MPa, 40 MPa and 42 MPa, respectively. As P91 can withstand stress intensity of 71 MPa at 570 °C for 2.7×10^5 hours (approximately 30 years), there's no risk of plastic collapse.

4.2 Inelastic Strain Indicator

The strain at the critical point is shown in Figure 5. The calculated maximum equivalent strain is 0.1%, and the maximum inelastic strain is 0.03%. Significant increase of inelastic strain only occurs during start-up. For the current depth of load change, the stress amplitudes cause mainly elastic strain and little inelastic strain.

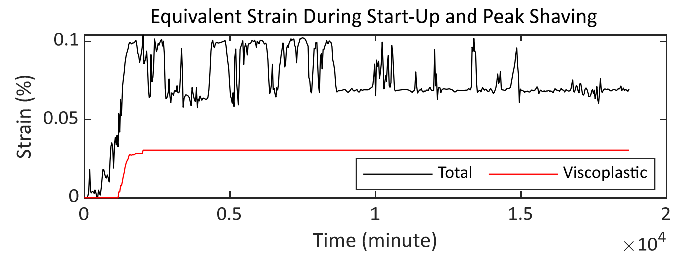
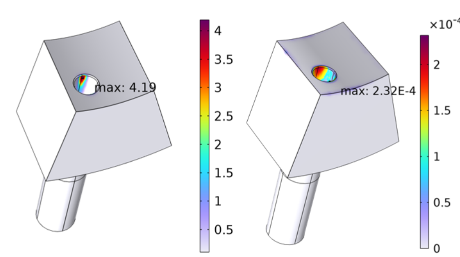


Fig. 5 Strain During Start-Up and Peak Shaving

4.3 Creep-Fatigue Indicator

The creep damage contour at the end of the operation is shown Figure 6 (a), from which it can be seen that the creep damage occurs only near the critical point. Creep damage accumulates mainly when the power unit operates at full load, as shown in Figure 7, because of higher stress. The creep damage at the critical point reaches 4.2% in the end. If the power unit operates at the same frequency and depth of peak shaving, the creep damage would exceed the defined limit after 300 days operation. It is suggested to consider increasing the fillet radius for lower stress, or allowing localized creep failure.



(a) (b)

Fig. 6 Creep and Fatigue Damage Contours (unit: %): (a) Creep Damage, (b) Fatigue Damage

Fatigue damage, as shown in Figure 6 (b), is quite low and also limited around the critical point. Most of the fatigue damage results from stress amplitude caused by peak shaving with the depth of about 50%, and the current temperature fluctuation amplitude would not cause significant thermal fatigue. The fatigue damage would be about 0.2% after 30 years of operation with the current frequency and depth of peak shaving.

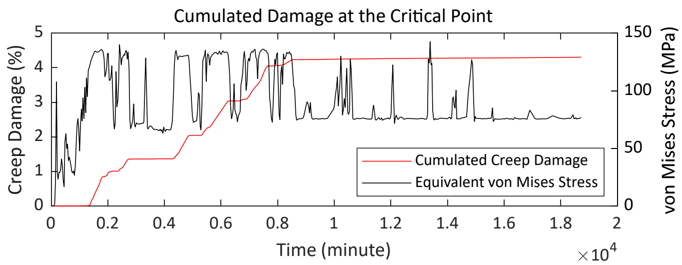


Fig. 7 Cumulated Creep Damage at the Critical Point

The creep-fatigue damage envelope is shown in Figure 8, where the red circle is the creep-fatigue damage indicator. The damage is within the limit when the indicator lies in the envelope curve. As the fatigue damage is quite small, it is practical to only consider the creep damage with the current frequency and depth of peak shaving. The asymmetry of the envelope indicates that the contributions of creep and fatigue to the final damage are different.

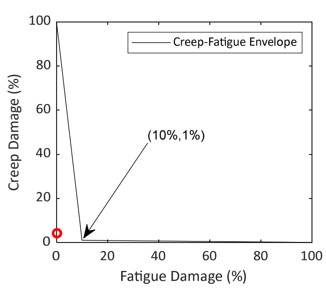


Fig. 8 Creep-Fatigue Damage Envelope

5. CONCLUSIONS

A lifetime estimation method for boiler components is proposed in this study, which takes the linearized stress and inelastic strain into consideration. The calculation results indicate that the influences of start-up process, current peak shaving depth (55%) and rate (1.4%/min) on the lifetime of the header at the outlet of the final-stage superheater are as follow:

(1) There's no risk of plastic collapse.

(2) Inelastic strain mainly accumulates during start-up process, rather than during peak shaving.

(3) Creep-fatigue damage mainly occurs around the fillets of the branch tubes. Under the current operating condition, the fatigue damage is only 0.2% after 30 years of operation, with no significant thermal fatigue. But the creep damage is excessive, exceeding the limit after operating for 300 days. Larger radius of the fillets may be needed, or localized creep failure could be considered acceptable.

The proposed method can be further improved by coupling fracture mechanics to investigate the impact of highly localized damage on other parts of the component, in order to avoid potentially excessively conservative lifetime estimation.

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